



Denali National Park & Preserve **GEOLOGY ROAD GUIDE**

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Capps · McLane · Chang · Grover · Strand

Credits

Former Denali geologist Phil Brease initiated this guide for the benefit of countless future staff and visitors. It is the product of multiple years' worth of efforts by National Park Service (NPS) staff and Geological Society of America (GSA) interns.

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The original edition of this book was inspired by the 2016 National Park Service Centennial during which Denali celebrated 100 years of geological research and exploration.



Dedication

This guide is dedicated to Phil Brease (Denali Park Geologist from 1986 to 2010).

Phil's humor, wisdom, music, and love of adventure and geology will never be forgotten by the many people whose lives he touched. Throughout his years as Denali's geologist, Phil discovered fossils, monitored glaciers and road hazards, reclaimed mined lands, taught geology, and predicted that if we kept looking in the right places, someday we would find a dinosaur track in the park.

Denali geology is no piece of cake, or one should say 'layer cake,' as places like the Grand Canyon are often described. In fact, I like to describe the geology of Denali as a mix of several well-known western parks. The recipe is to place the sediments of the Grand Canyon, the plutonic rocks of Yosemite, and the volcanics of Mount Rainier in a blender, and turn it on briefly to 'chop.' Then layer as a parfait, and serve with large quantities of ice from the likes of Glacier Bay National Park!

—Phil Brease



NPS Photo

Table of Contents

Part 1

From Old Rocks to Young Ice: Entrance Area to Teklanika	1
Mount Healy	6
Glacial Forces	7
Glacial Erratics	8
Drunken Trees	9
Hines Creek Fault Expression	10
Lignite/Dry Creek Terminal Moraine	11
The High One Emerges	12
Gossan	13
Gravel Ridge	14
Savage River	16
Nenana Gravel	18
Double Mountain	19
Antecedent Stream	23
Drunken Forest	24
Kettle Ponds	25
Teklanika River and Surrounding Area	28

Part 2

Dynamic Denali: Teklanika to Toklat	29
Where Teklanika and Cantwell Formations Meet	32
Teklanika Dikes	33
First Dinosaur Footprint Found In Denali	36
Tattler Creek	37
Igloo Creek Debris Slide	40
Sable Pass Debris Slide	42
Coal Mining by the East Fork Toklat	43
Polychrome Pass	44
Bear Cave Slump	46
Building the Park Road	47
Pretty Rocks Landslide	48
Spheroidal Weathering	50
Polychrome Overlook—Looking North	51
Polychrome Overlook—Looking South	52
Patterned Ground	55
Road-Blocking Debris Flows	58
Toklat River	59

Part 3

A Park of Unusual Scale: Toklat to Kantishna	60
Highway Pass	64
Bergh Lake	65
Denali Unobscured	67
Eielson Visitor Center	68
Pillow Basalt	71
Muldrow Glacier	72
Hines Creek Fault	74
Muldrow Moraines	75
Western Kettle Ponds	76
Wonder Lake	77
Glaciofluvial Terraces	80
Seismic Activity in the Kantishna Hills	81
Kantishna Area Mining Legacy	82

Geo Features

Rock Types	4
Braided Rivers	15
Aufeis	22
Assembling Alaska: Accreted Terranes	26
Paleontological Wonders	34
Precarious Permafrost	38
Glaciers	56
Why is Denali so Tall?	70
Earthquakes	78

Geologic Timeline	84
--------------------------------	----

Glossary	85
-----------------------	----

References	88
-------------------------	----

Index	94
--------------------	----

Introduction

Denali National Park and Preserve is a place where powerful geologic forces—tectonics, volcanism, and glaciation, among others—have collectively produced a stunning showcase of landscape features. Some features dominate, like the flanks of Denali and the glacially-carved valleys that surround it, while others may only be noticed by the trained eye. This guide highlights some of the most interesting geological phenomena that can be experienced from the Denali Park Road. It stands on the shoulders of several past road guides, including some by the previous park geologist, Phil Brease^{10,48}. Though the text is composed with an east-to-west drive in mind, each feature stands alone, allowing for the guide's use regardless of where you are or how you got there.

If you are new to the field of geology or to Denali, you may want to read the GEOFeatures first, as they cover broad topics such as rock types, how Alaska and the Alaska Range were formed, braided rivers, paleontology, glaciers, and earthquakes. Skimming the glossary will also make the text more understandable for those unfamiliar with geology terminology. For readers with physical science backgrounds, be aware that some geologic names (terrane, glaciation, and such) are capitalized in non-conventional ways to aid comprehension for the layperson.

The text is divided into three sections that group geologically-similar areas and roughly divide the Denali Park Road into thirds. Each section opens with an overview map and contains mile-by-mile feature descriptions, GEOFeatures, and fun facts.

Through this book, we invite you to celebrate 100 years of geologic research and exploration in Denali National Park and Preserve. In 2016 and 2017, the National Park Service and Denali celebrated back-to-back Centennials. Both birthdays honor the researchers and rangers who have dedicated themselves to understanding and stewarding America's special places. We hope you enjoy exploring Denali geology through these pages and in person, and by doing so, help us launch another 100 years of learning and conservation.



PART From Old Rocks to **—1—** Young Ice

Park Entrance to Teklanika

For the first 30 miles, the Denali Park Road parallels the Hines Creek Fault while winding between the Outer Range to the north and the foothills of the far larger Alaska Range to the south. This portion of the road showcases geologic wonders ranging from the oldest rocks in the park to modern permafrost features. The Outer Range is composed of rocks that have been metamorphosed by multiple episodes of compression and heat. Much more recently, glaciers carved the valleys through which the road winds, transported huge amounts of debris, and left behind erratics and other evidence of their passage. While these particular glaciers are now gone, the ground is still permanently frozen beneath portions of the taiga and tundra ecosystems through which you will soon travel. However, climate change is starting to thaw Denali's frozen ground, with tangible impacts on trees, roads, and infrastructure.

Mile Feature

0–15	Mount Healy
2.4	Glacial Forces
3–5	Glacial Erratics
3–8	Drunken Trees
7.1	Hines Creek Fault Expression
8.3	Moraine of Lignite/Dry Creek Glacial Advance
9–13	The High One Emerges
13.5	Gossan
13.9	Gravel Ridge
14.7	Savage River
18.6	Nenana Gravel
19.7	Double Mountain
22.8	Antecedent Stream
23.5	Drunken Forest
28.8	Kettle Ponds
30.2	Teklanika River and Surrounding Area





G E O Rock Types

FEATURE Three major types of rocks make up Earth's crust: igneous, sedimentary, and metamorphic.

Igneous rocks are formed when molten rock solidifies. When magma cools slowly deep within the earth, the resulting rocks—granite being a classic example—are classified as intrusive. When magma cools rapidly at or near the surface, often as lava emerging from a volcano, it is classified as extrusive. Basalt, rhyolite, and andesite are common types of extrusive igneous rocks. All igneous rocks are characterized by crystalline structures. Intrusive rocks tend to have large crystals, while extrusive rocks have small, often indiscernible crystals.

Igneous rock formations described in this guide include the Teklanika Formation and Mount McKinley Granite.

Below: Plant fossils in a sedimentary rock tell us about the park's past.



NPS Photo / Tim Rains

Above: Igneous rocks give Polychrome Pass its iconic multi-hued tones.

Sedimentary rocks are derived from sediments—particles of mineral and organic material that have been deposited by water or wind. Sediments are commonly carried by rivers or streams and deposited in basins such as lakes and seas. These sediments are often buried and compressed into rock. Typical sedimentary rocks

include sandstone, limestone, shale, and chert. Fossils found in sedimentary rocks provide clues to the environment in which the sediment was deposited.

Sedimentary rock formations described in this guide include the Cantwell Formation, Kahiltna Flysch, the Usibelli Group, and Nenana Gravel.



Metamorphic rocks are preexisting rocks that have been changed due to intense heat and/or pressure without completely melting. The original rocks can be sedimentary, igneous, or even metamorphic. When rocks are squeezed and baked beneath Earth's surface or by contact with magma, minerals may be replaced or the rock may change texture. Typical metamorphic rocks around Denali include schist, slate, and marble.

The Yukon-Tanana Terrane is the only metamorphic group of rocks described in detail in this guide. Four other terranes found in Denali (see p.26) also contain metamorphic rocks.

MILE Mount Healy

0–15 The park entrance area is dominated by Mount Healy, which looms just north of the park road. Though Mount Healy is referred to as one mountain, its ridgeline actually extends for 15 miles (24 km) from the George Parks Highway to the Savage River. Mount Healy is part of the informally named Outer Range, which also includes Mount Margaret and Mount Wright to the west of the Savage River.

The foundation for the entire Outer Range is the metamorphic Yukon-Tanana Terrane. Terranes are

fragments of the Earth's crust that have been scraped or broken off of one tectonic plate and sutured onto another. The rocks of this terrane, the oldest that you'll find in the park, formed ~400 million years ago as shallow-water seafloor deposits and were intruded by igneous rocks ~365 million years ago^{23,29}. In the Early Jurassic Epoch (~195 million years ago), these rocks were accreted onto the North American continent. Since then the Yukon-Tanana rocks have experienced multiple episodes of regional metamorphism^{3,45}.

The Yukon-Tanana Terrane is the foundation for roughly the northern third of the park and many of the nearby mountains that line the George Parks Highway, including Sugarloaf Mountain northeast of the park entrance. The Yukon-Tanana Terrane extends northwards to the Brooks Range and makes up the hills surrounding Fairbanks, as well as east into Canada⁵⁶.

Below: The Mount Healy ridgeline provides breathtaking views of the park.

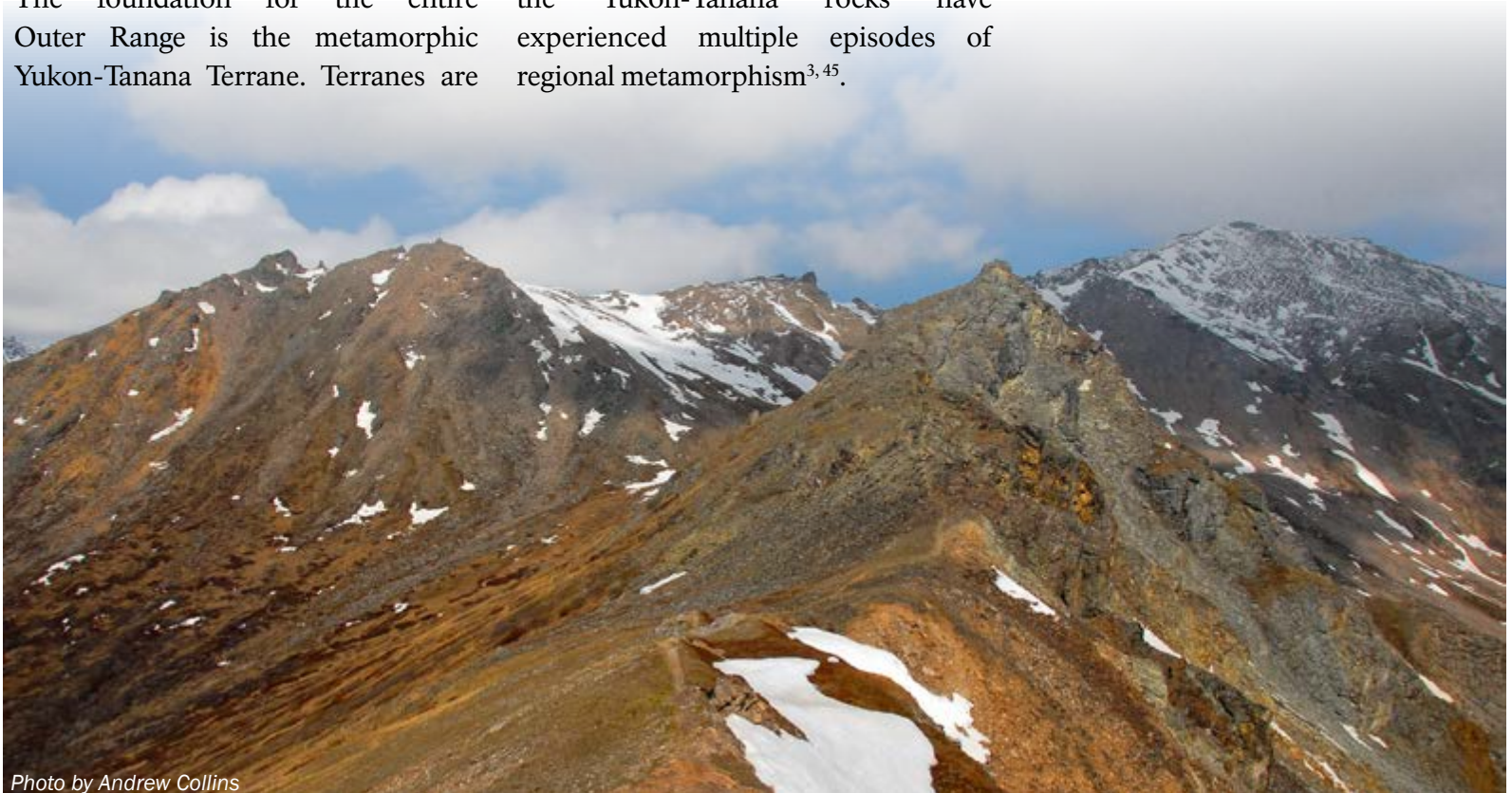


Photo by Andrew Collins

MILE Glacial Forces

2.4 Look around and imagine the vast amounts of ice—thousands of feet thick and miles long—required to shape the landforms that you see ice-free today. As recently as 22,000 years ago, much of this area would have been covered in glacial ice.

During the last ice age, glaciers advanced north from the Alaska Range into the current Nenana River valley during four major glaciations: the Teklanika Glaciation ~2.8 million years ago⁷², the Browne Glaciation during the mid-Pleistocene (numerical age unknown, but >300,000 years ago²⁷), the Lignite/Dry Creek Glaciation ~500,000 years ago⁴⁴, and the Healy Glaciation ~65,000 years ago^{27,14}.

From this bend in the road, look east past the railroad trestle to where the Nenana River flows in the distance. Approximately 22,000 years ago, the much younger and smaller Riley Creek Glaciation would have terminated here¹⁴. The terminal moraine still lies immediately to the right (south) of the train trestle, but is largely obscured by vegetation. The Riley Creek Glaciation was likely a re-advance of the more extensive Healy Glaciation⁸⁰.

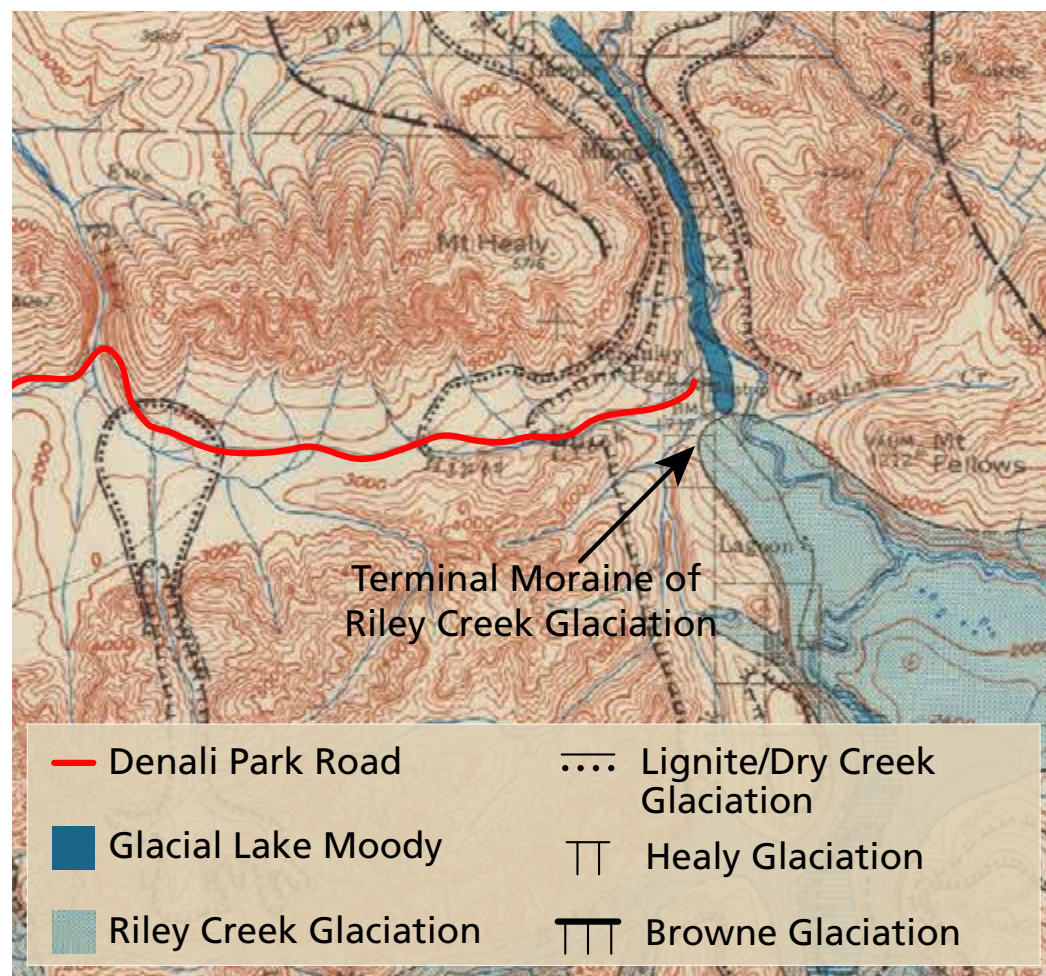
The Healy Glaciation is named after a terminal moraine south of the town of Healy. As the glacier receded,

meltwater that was dammed behind the Healy moraine and a bedrock ridge formed the 400-foot (122 m) deep, 11-mile (18 km) long prehistoric Lake Moody in the valley between Healy and the park entrance⁸⁰. Lake Moody has long since drained, but evidence of its existence is still apparent in unstable

landforms that cause severe problems for the railroad, highway, and buildings in the Nenana Canyon.

A lobe of the Healy glacier flowed uphill from the main north-south valley, depositing the till (glacial sediment) that Park Headquarters at Mile 3.4 is built on.

Below: Map of glacier extents around the park entrance during the last ice age⁸⁰.



MILE Glacial Erratics

3–5 The rock next to the sign for Park Headquarters (Mile 3.4) is a foreigner in Denali. It's a glacial erratic—a rock transported by a glacier and often, but not necessarily, made of material exotic to its surroundings. You can sometimes track an erratic's origin based on its mineral composition.

On nice days you can see two more erratics at the top of the hill to the south behind Park Headquarters. Notice how unusual they are in both size (more than 30 feet [10 m] wide) and shape compared to their smooth, glacially-scoured surroundings. Upon closer inspection, you'd notice that the erratics are granitic.

However, the closest bedrock outcrop of granite is many miles away. This means that during the Dry Creek Glaciation several hundred thousand years ago, these rocks traveled many miles on a lobe of ice and were dropped in their present locations when the ice beneath them melted^{80,11}.



MILE Drunken Trees

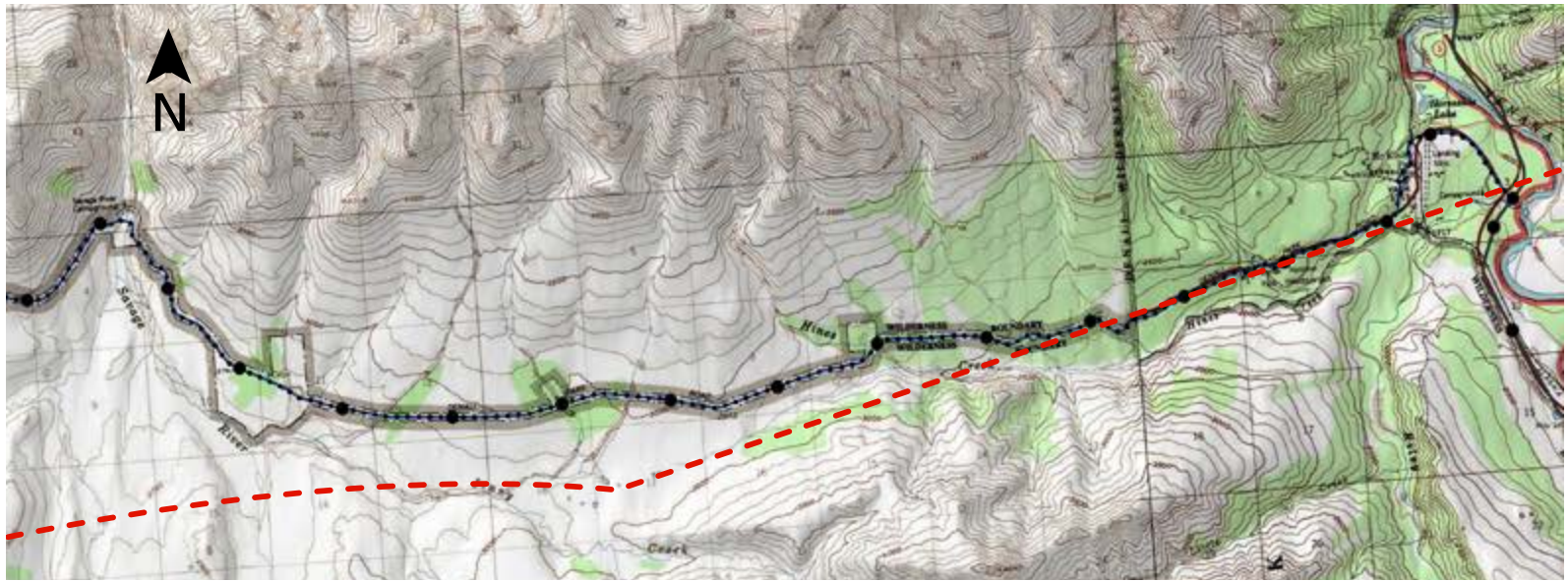
3–8 In the forests on both sides of the road, you may notice a few leaning trees. Originally upright, some of the trees in this area are now tipping over as a consequence of thawing permafrost. The trees are rooted in a shallow top layer of soil that thaws seasonally; this soil is referred to as the ‘active layer’. When the permafrost underneath the active layer thaws, the trees have very little root depth to help them remain upright on the newly unsupported ground. The result is that the trees look like they’ve had a little bit too much fun.

Drunken forests (a real scientific term!) are often found by roadsides or lakes, where heat is more easily transferred into the frozen ground. Throughout the park, black spruce is the tree species most typically found in drunken forests because it is tolerant of the water-saturated soils often found on top of permafrost. While you may see a few leaning trees here, Mile 23.5 near the Sanctuary River provides a better example of a drunken forest.

Right: Tipsy trees occur intermittently along the park road to the west of Park Headquarters.



NPS Photo / Denny Capps



MILE Hines Creek Fault

7.1 Here the road crosses Hines Creek and travels parallel to a regionally-important geologic feature, the Hines Creek Fault. This fault is an active part of the larger Denali Fault system that arcs east-west across the state. While the fault gets its name from the creek, the creek itself is a fault-controlled drainage, meaning that it follows the path of the fault and probably wouldn't exist if it weren't for the weakened material caused by tectonic activity.

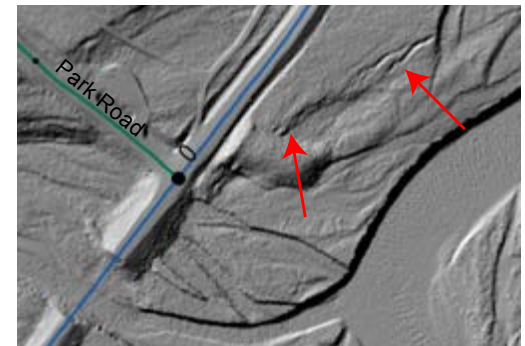
The Hines Creek Fault trends between the park road and the Alaska Range foothills to the south, acting as a boundary between two terranes—the Yukon-Tanana Terrane to the north and the Pingston Terrane to the south⁶⁹.

Above: The Hines Creek Fault appears as a dotted red line just south of the Park Road on this annotated USGS topographic map⁶⁹.

However, glaciations, landslides, stream deposition, and other geologic processes have left the fault largely invisible here.

Near the park entrance, visible but out of view from the park road or any trail, lies a recent (~1,300-year-old) scarp of the Hines Creek Fault³². This specific fault scarp remained unnoticed, because vegetation obscured its location, until 2011 when a LiDAR (Light Detection and Ranging) survey allowed the Earth's surface to be seen in intricate detail. This imagery revealed that the fault trends directly underneath the northern abutments of the Riley Creek bridge on the Parks

Highway. Luckily this was discovered in time for the new Riley Creek bridge, built in 2015, to be designed to accommodate offset from the fault.



Above: 2011 LiDAR image of entrance area showing Hines Creek Fault (red arrows), Park Road (green), and Parks Highway (blue).

MILE Lignite/Dry Creek

8.3 Terminal Moraine

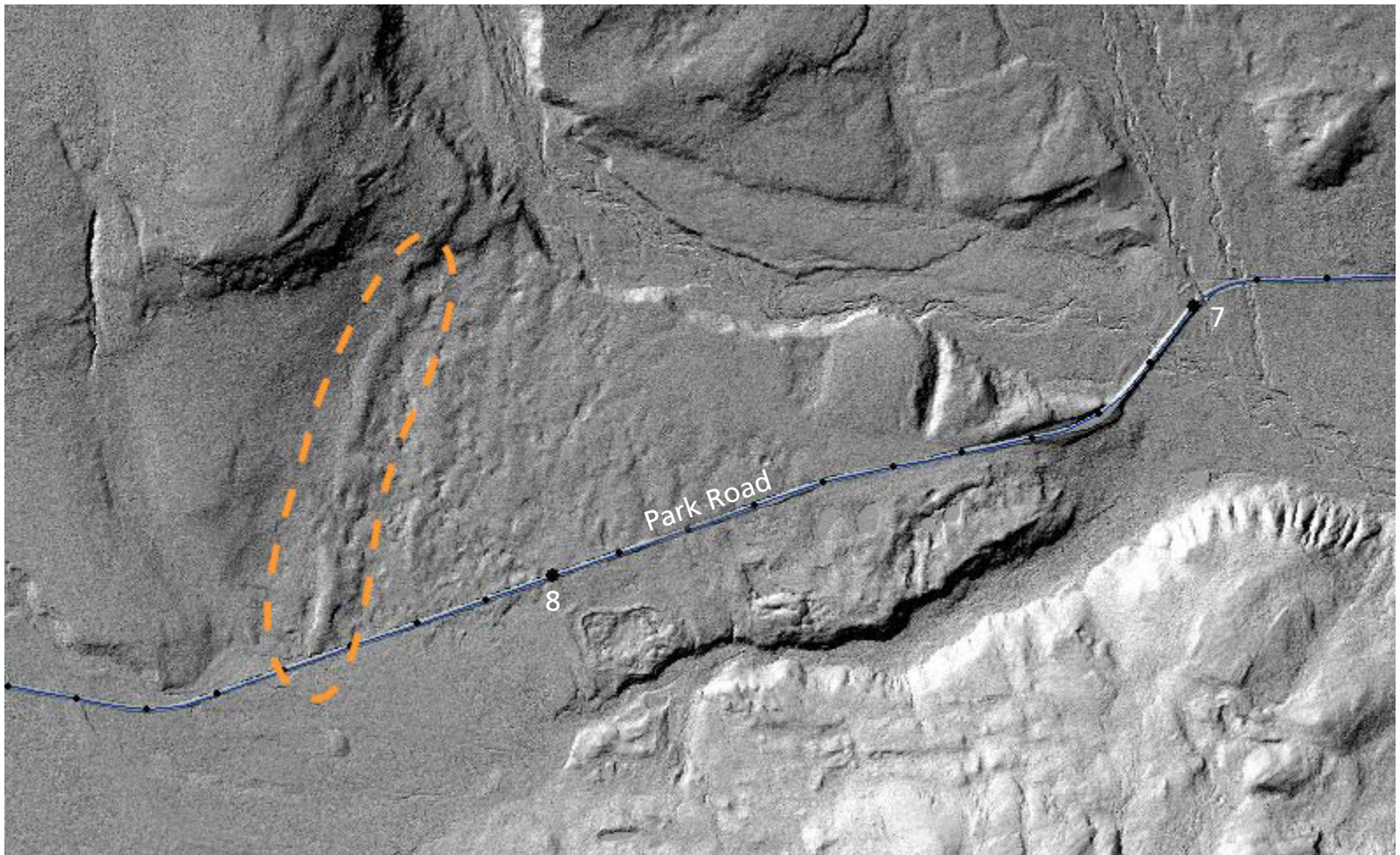
Here the road cuts through the terminal moraine of the Lignite/Dry Creek Glaciation which flowed westerly, and uphill, from the Nenana River valley ~500,000 years ago^{44,80}. This uphill glacial flow illustrates the tremendous mass and power of the parent glacier,

from which the lobe that left behind this moraine was merely an offshoot.

The moraine is not obvious from the ground because so much time has passed since its deposition. Erosion and vegetation now obscure its presence.

However the feature stands out clearly on a digital terrain model, which is a 3D representation of the Earth's surface without vegetation. It is also illustrated in the figure on page 7.

Below: The terminal moraine of the Lignite/Dry Creek Glaciation is the low, thin ridge outlined by the orange dotted line on this 2010 IFSAR digital terrain model.



MILE The High One Emerges

9–13 Here you may catch your first view of Denali to the southwest if the weather is fair. White-capped and still 76 miles (122 km) away, the mountain will appear large, but not particularly taller than other nearby peaks. That's a deception of perspective; at 20,310 feet (6,190 m) Denali is over 14,000 feet (4,300 m) taller than

Double Mountain and the other mountains that you see in the foreground.

A pullout at Mile 10.5 is the first safe place to admire the view, and Mountain Vista rest stop at Mile 12.6 is one of the better places to enjoy mountain gazing along this stretch of road. On a

clear day the mountain will get closer and appear bigger until you reach Wonder Lake, where the summit will only be 26 miles (42 km) away... but remember, that's as the crow flies. It takes most of the few, hardy mountaineers who climb Denali starting from Wonder Lake each year a month to make the round trip.





MILE Gossan

13.5 The orange rock outcrop on the hill just north of the road is called a gossan. The coloring is caused by oxidization of iron-sulfide minerals within Yukon-Tanana rocks—rust! Outcrops like this one oxidize into eye-catching hues when exposed to surface conditions and attract the attention of prospectors looking for gold, silver, lead, zinc, and other economically valuable resources because gossans often indicate the upper part of ore deposits. This particular area was worked by prospectors, possibly in the 1920's and 1930's, but was eventually abandoned¹³.

MILE Gravel Ridge

13.9 Just across the Savage River to the west is a mid-valley ridge with exposed sediment at the northern end. The genesis and evolution of this ridge and its surroundings is a point of ongoing research. Some have interpreted it to be an esker, which is a deposit from a stream running under or through a glacier¹¹. Others have interpreted it as a remnant moraine of the Lignite/Dry Creek glacial advance from about 500,000 years ago^{44,80}.

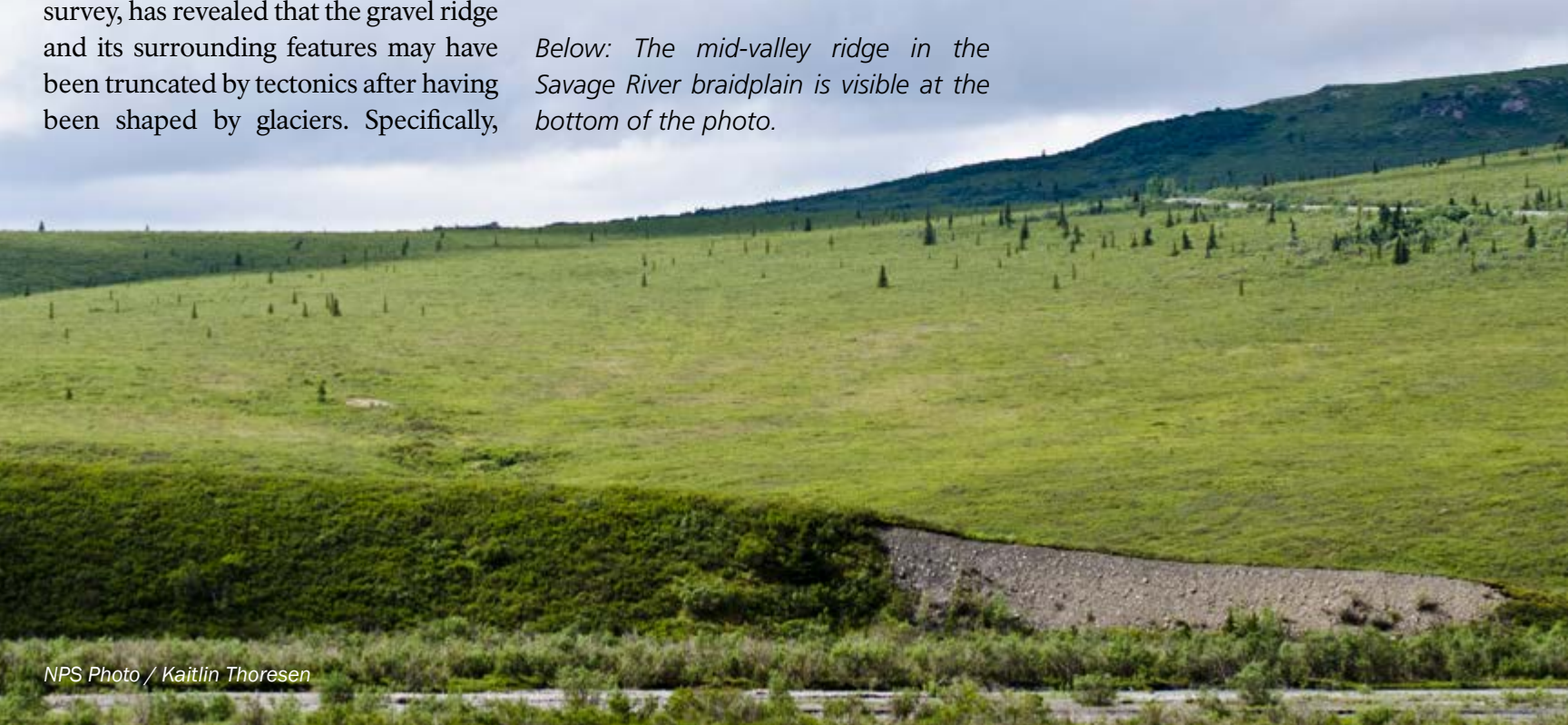
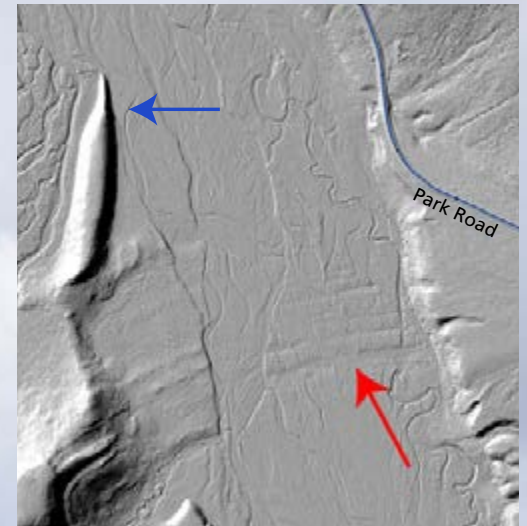
LiDAR data collected in 2005, which measured the topography of this area in far greater detail than any previous survey, has revealed that the gravel ridge and its surrounding features may have been truncated by tectonics after having been shaped by glaciers. Specifically,

recent faulting may have caused linear striations in the stream sediments⁶.

Ultimately these landforms are the result of several geologic processes interacting through time. The evolution of this story illustrates how modern technologies such as LiDAR are casting new light on old geologic mysteries here and elsewhere in the park.

Right: Lineations (red arrow) possibly indicate tectonic shaping of the area. The exposed sediment in the photo below is located near the upper left of this digital terrain model (blue arrow).

Below: The mid-valley ridge in the Savage River braidplain is visible at the bottom of the photo.



G E O Braided Rivers

FEATURE Many of the rivers and streams in Denali are braided, consisting of many short-lived channels weaving across a wide bed of cobbles, gravel, sand, and silt. What you are seeing is not just a “dry phase”—water almost never flows over the entire width of a braided river at any one time. Braided rivers and streams occur within watersheds where relatively large amounts of sediment are transported by relatively small amounts of water. Because glaciers

are such powerful agents of erosion and therefore create large amounts of sediment, braided rivers are classically, although not exclusively, glacially-fed.

At higher water levels, braided rivers can transport larger amounts of sediment from upstream, but they deposit that sediment when the water level drops and slows. The deposited sediments force the water to move to new paths of less resistance. In Denali, this often happens on a diurnal basis,

with higher water flows and sediment transport occurring during the heat of the day when snow and ice is melting and contributing to flow, but it also varies seasonally and in response to storms and glacial processes.

Watch for river braids as you cross the Savage (Mile 14.7), Teklanika (Mile 30.2), and Toklat (Mile 53) rivers, from Polychrome Overlook (Mile 45.8), and from Eielson Visitor Center (Mile 67), among other locations.

Below: The braids of an unnamed stream weave through Denali's lush landscape.



Photo by Diane Kirkendall



NPS Photo / Tim Rains

MILE Savage River

14.7 Savage River is one of several braided rivers in Denali that are characterized by transitory channels meandering across wide beds of sediment over time. However this behavior is not the result of glacial melt, as is the case for most braided rivers in the park, because no glaciers remain in the Savage River watershed. Savage River is braided because of high sediment input from brittle rock, and from a relative lack of vegetation stabilizing its headwaters.

An important transition zone that illustrates the glacial history of this area is located about halfway between the Savage River vehicular bridge and the Savage River Loop Trail footbridge to the north. Upstream (south) from this point, Savage River runs wide and shallow in a U-shaped valley typical of glacial scouring. Downstream (north), Savage River runs fast and restricted through a V-shaped valley typical of river erosion. Look for these distinctive shapes as you cross the

vehicular bridge¹¹. While more extensive glaciations have affected the topography of the canyon in the past, they occurred over two million years ago²⁷. The river has therefore had substantial time to erode the V-shaped canyon that we see today.

Above: The view south from the Savage River vehicular bridge in the fall. This portion of the river flows through a valley shaped by past glaciations.



Left: The view north from the Savage River vehicular bridge shows a V-shaped valley resulting from river erosion. This topography is different from the glacially-sculpted terrain seen on page 16.

FUN FACT: Savage Rock (photo below), the jagged outcrop that you can walk to just uphill from the Savage River parking lot, is a surprising stumper. Why this outcrop is so prominent compared to its surroundings—despite being made of similar rocks—remains a mystery. One theory is that faulting caused the rock to protrude from the surrounding topography. A second is that it slid down from above. Or Savage Rock could be made of more resistant schist than the surrounding metamorphic rock. Further studies are needed to resolve this enigma.

The Savage River canyon is one of the few places where erosion has exposed the Yukon-Tanana Terrane bedrock along the road. Take a closer look and you'll notice large amounts of mica-quartz schist, a shiny rock that gets its sparkle from the flaky mineral sericite and quartz veins. The varieties of metamorphic rock in the Yukon-Tanana Terrane, along with the degree to which they have been folded and faulted, attest to the terrane's age and dynamic history.



Photo by Diane Kirkendall



NPS Photo / Lian Law

MILE Nenana Gravel

18.6 The Alaska Range experienced the majority of its uplift in the last six million years. Scientists have deduced the timing of this impressive tectonic episode partially thanks to the humble Nenana Gravel formation that outcrops here on the north side of the road. The Nenana Gravel is a ~4,000-foot thick (1,200 m) sedimentary formation composed mostly of loosely-consolidated gravel and sand. These sediments are from igneous and sedimentary parent rocks that match the lithology (physical characteristics) of rocks in the Alaska Range. The Nenana Gravel formation is often underlain by a ~2,000-foot thick (600 m) group of sedimentary formations called the Usibelli Group, the sediments from which match parent rocks from the metamorphic Yukon-Tanana Terrane to the north⁶¹.

The fact that the Nenana Gravel overlies the Usibelli Group in the Tanana Basin—a large, low area on the north side of the Alaska Range—is one of the primary ways that scientists know when the uplift of the Alaska Range began. Leaf fossils, pollen, radiometric dates, and tectonic evidence from the two formations demonstrate that the Usibelli Group sediments washed into the Tanana Basin from the north mostly during the Miocene Epoch (5–23 million years ago). Around six million years ago, these sedimentary layers started being buried by Nenana Gravel sediments flowing in from the south. This shift in sediment source indicates when the Tanana Basin was tilted north by the newly rising Alaska Range^{61,75}. Sediment deposits continue to accumulate in the Tanana Basin today as the Alaska Range continues to rise.

Above: A park shuttle bus approaches a Nenana Gravel outcrop to the west of the Savage River. The summit of Denali peaks out from behind the ridge on the left.

FUN FACT: The Usibelli Group of formations is mined for coal 11 miles (18 km) north of the park entrance near the town of Healy. The lignite coal dates to the Miocene and is evidence of a time when Denali's environment consisted of swampy bogs and vast forests, a drastic departure from today's boreal forest and alpine tundra⁴¹! The Usibelli Coal Mine is currently the only active coal mine in the state. The coal, notable for its low sulfur content, is transported to power plants in interior Alaska as well as exported to South Korea and Chile⁷⁸.

MILE Double Mountain

19.7 To the south lies the broad north slope of a mountain with a jagged, indistinct summit—Double Mountain. The mountain is capped by the colorful Teklanika Formation, a Tertiary (55–60 million years ago) volcanic rock unit²¹. The base of Double Mountain is composed of the Cantwell Formation, a late Cretaceous (~70 million years ago) sedimentary rock unit, and is intruded by the overlying Teklanika Formation²¹.

It is noteworthy that the Teklanika Formation rocks are similar in age and mineral composition to those of the Mount McKinley Granite, which comprises many of the highest peaks in the Alaska Range, including Denali. The two rock units have very different appearances because the volcanic rocks

cooled relatively quickly at the surface and therefore have a finer texture, while the granitic rocks cooled very slowly many miles deep in the crust and have a relatively coarse crystalline structure.

The Teklanika volcanic eruptive center was near Denali's peak, as demonstrated by the direction that the volcanic conglomerate flowed. This directionality is interpreted by researchers based on the orientation

of clasts, or fragments, in the conglomerate. Some of the Teklanika clasts are enormous (40 feet or 12 m across), and were violently erupted out of a volcano during an event similar to the Mount St. Helens eruption of 1980 (figure p.21). Also visible is a whitish tuff, or ash layer, dipping at an angle near the upper third of Double Mountain. This 30-foot (9 m) thick tuff is the result of many thinner ash deposits accumulating over time²⁰.



Above: A sample of McKinley Granite, an intrusive rock.

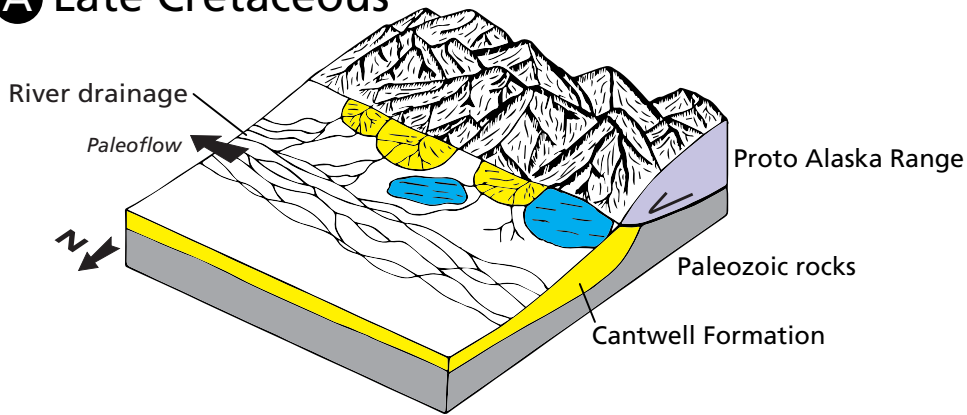


Above: A sample of Polychrome rhyolite, an extrusive or volcanic rock.



Above: Double Mountain (left) looks shaded in the early morning light while Denali looks pinkish and hazy in the background.

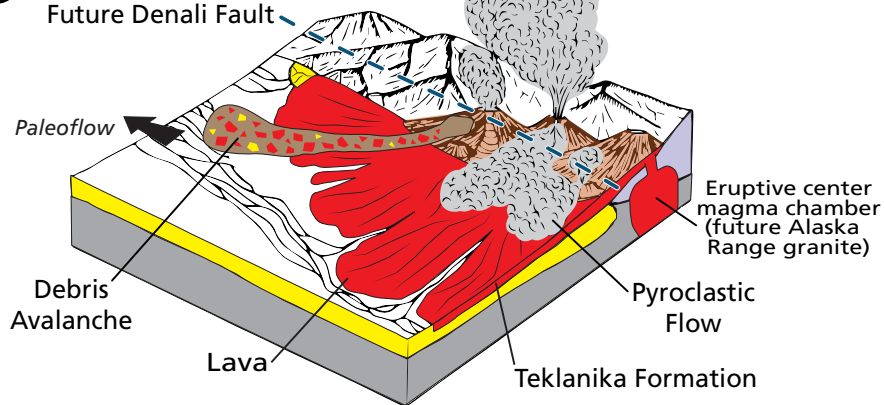
A Late Cretaceous



Left: Diagrams showing the depositional and tectonic history of the Denali area before, during, and after Teklanika volcanism²⁰.

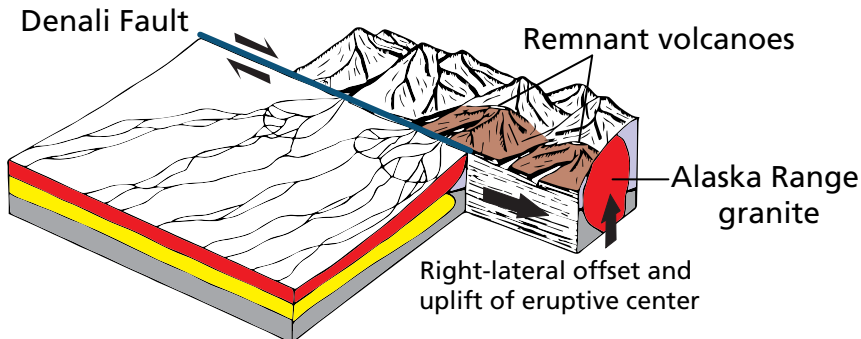
A) The Cantwell Formation was deposited into the Cantwell Basin on the north side of the Alaska Range ~70 million years ago (late Cretaceous) during a time of active tectonics.

B Late Paleocene



B) Teklanika volcanic rocks erupted from the southwest of their present location 55–60 million years ago and were deposited on top of the Cantwell Formation.

C Post-Early Eocene



C) Subsequent right-lateral strike-slip movement along the Denali Fault then displaced the Teklanika rocks to the northeast relative to their eruptive center. The McKinley pluton (comprised of Mount McKinley Granite) may represent the uplifted roots of the Teklanika eruptive center.



Photo by Lyn Topinka



NPS Photo / Lian Law

Above: This large boulder (inset left) is a clast, or fragment, on Double Mountain (main photo) that is thought to have been deposited by volcanic mud that flowed out of the Teklanika eruptive center. Similar mudflows deposited huge boulders (inset right) far from the volcanic vent of Mount St. Helens during its 1980 eruption²⁰.



NPS Photo / Sierra McLane

G E O Aufeis

FEATURE Depending on when you visit, you may see flows of ice along the park road that formed in the winter. Called aufeis or overflow, this ice usually forms in Denali when very cold temperatures freeze surface water, thereby sealing in the groundwater below. Over time (minutes to days), pressure builds up until the surface ice cracks and the groundwater flows upward onto the surface, creating a new ice layer on top.

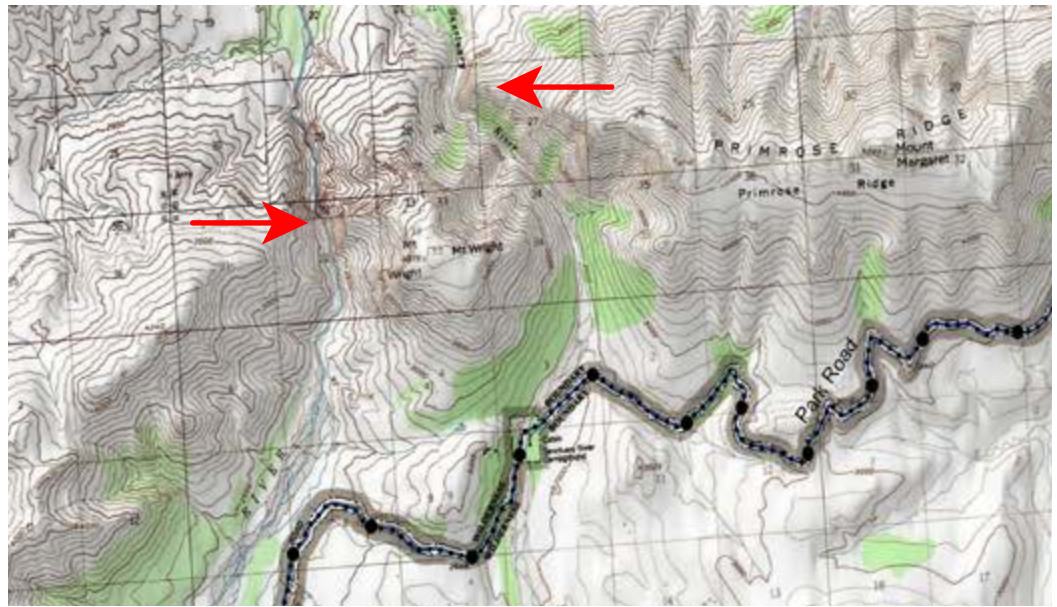
Overflow events occur repeatedly throughout Denali's long winters, building up ice layers to depths of six feet (2 m) or more. This phenomenon is limited to high-latitude areas. While often occurring in the same places annually, aufeis will typically melt when exposed to warm summer temperatures. Through June you may see aufeis in the Teklanika River channel (Mile 30.2), other streams and rivers, and along the road (Mile 4.4).

Above: Aufeis engulfs a bridge along a hiking trail near the Denali Visitor Center, making it practically impassable. Aufeis is one of the larger obstacles that trail and road crew workers face in Denali.

FUN FACT: Aufeis is a German word, meaning "ice on top." It is the combination of auf, meaning 'on' or 'upon', and eis, meaning 'ice'.

MILE Antecedent Stream

22.8 Look north—do you find it odd that the Sanctuary River below you is cutting north through the Outer Range rather than flowing east out the wide valley through which the park road winds? Sanctuary, as well as Savage (Mile 14.7), and Teklanika (Mile 25.5) rivers, are all antecedent streams, meaning that they occupied their current, north-flowing courses prior to the uplift of the Outer Range. Antecedent streams (ante meaning ‘before’ and cedent meaning ‘occurrence’) cut their channels at the same rate or faster than uplifting land rises around them, making them appear to defy the physical law of water following the path of least resistance.



Above: The red arrows point to the Teklanika (left) and the Sanctuary (right) rivers, both of which have flowed north since before the uplift of the Outer Range.

Below: The Sanctuary River cuts north through the Outer Range.



NPS Photo

MILE Drunken Forest

23.5 Here to the east of the road is a good place to see a grove with many tipsy trees. Remember, drunken forests are often the result of thawing permafrost, and indeed that is the case here. The stunted, drunken forest in the foreground transitions to tall trees, and then to no trees at all in the active channel of the Sanctuary River (which flows north [left] from where it is barely visible at the right edge of the photo). The taller trees are thriving in permafrost-free ground that was warmed by the river when it flowed nearer to the road in the relatively recent geologic past. In contrast, the stunted trees are limited by the shallow permafrost that restricts root depth and consequently tree height.



Photo by Alina Motschmann



MILE 28.8 Kettle Ponds

Along this stretch of road you'll see several kettle ponds through the trees to the east—little remnants of glaciations past. Kettle ponds are formed when large blocks of glacial ice are separated from the main ice mass and are buried by glacial outwash sediments. When the ice melts, it leaves behind a depression, which

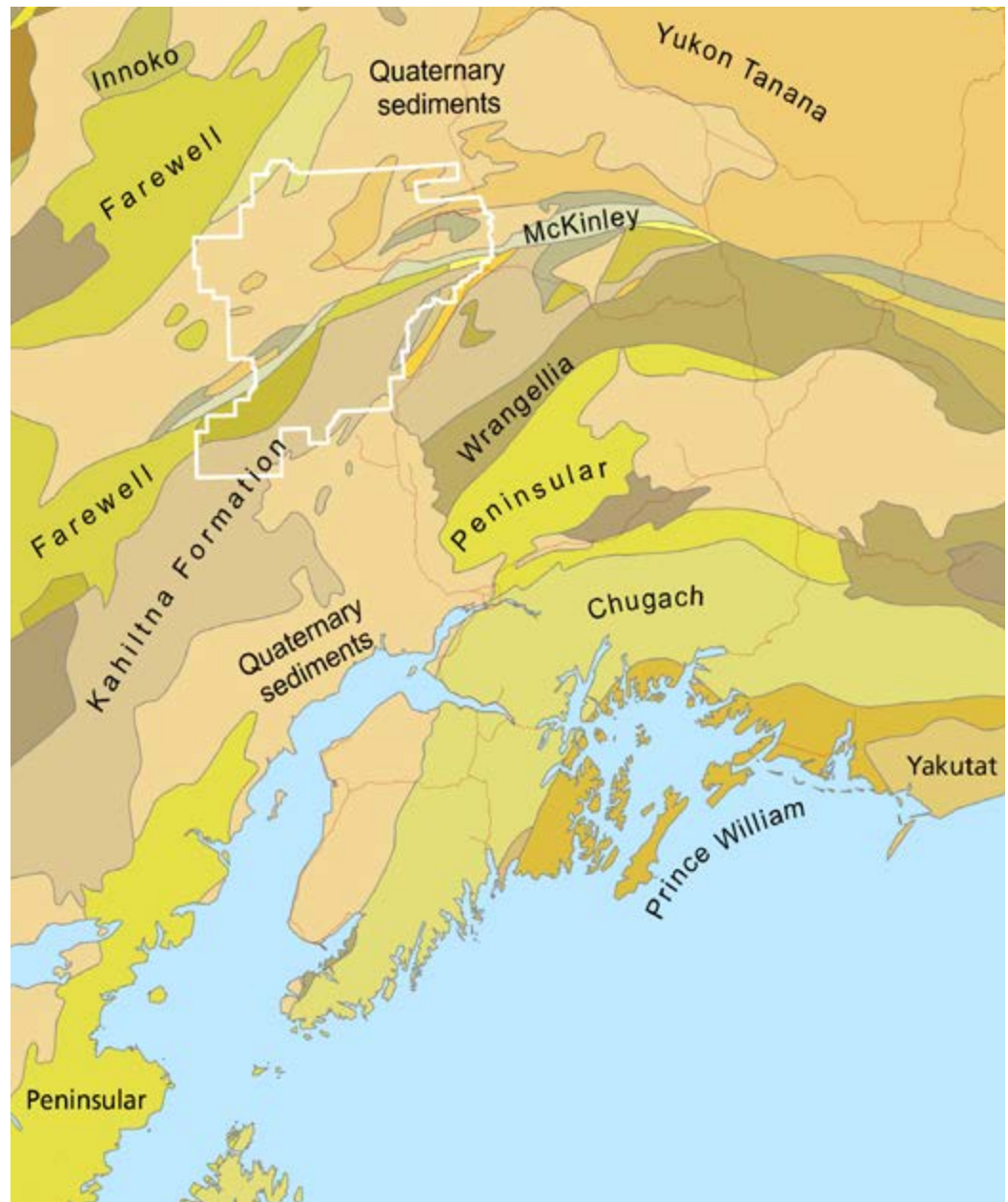
then often fills with precipitation, groundwater, or surface water. Kettle ponds are generally distinguishable by their small size and shallow depth. These kettles were likely formed during the retreat phase of the Riley Creek Glaciation which reached its maximum extent approximately 22,000 years ago^{27,44}.

GEO Assembling Alaska: **FEATURE** Accreted Terranes

Both politically and geologically, Alaska is a young state. Most of Alaska's current landmass was not originally part of the North American continental plate. Almost all of the state is composed of accreted terranes, regions of geologic material that have scraped or broken off of one tectonic plate and piled up on another during convergence. Alaska's terranes range in origin from previously isolated oceanic volcanic island arcs (think: Aleutian Islands) and microcontinents (think: Madagascar) to rocks formed on ancient sea floors⁶⁹.

Plates carried these rocks towards the edge of the small sliver of northeastern Alaska that was originally part of the North American Plate. The transported material was then plastered and crumpled up against the edge of the plate, like snow in front of a snowplow, as the oceanic plate subducted under the continental plate. Thus, in general, older terranes are found farther north and younger terranes farther south in Alaska⁶⁹.

Terranes have been accreting onto Alaska for about 200 million years, with oceanic plates serving as conveyor belts for the accreted rocks. Today the Pacific Plate is ramming

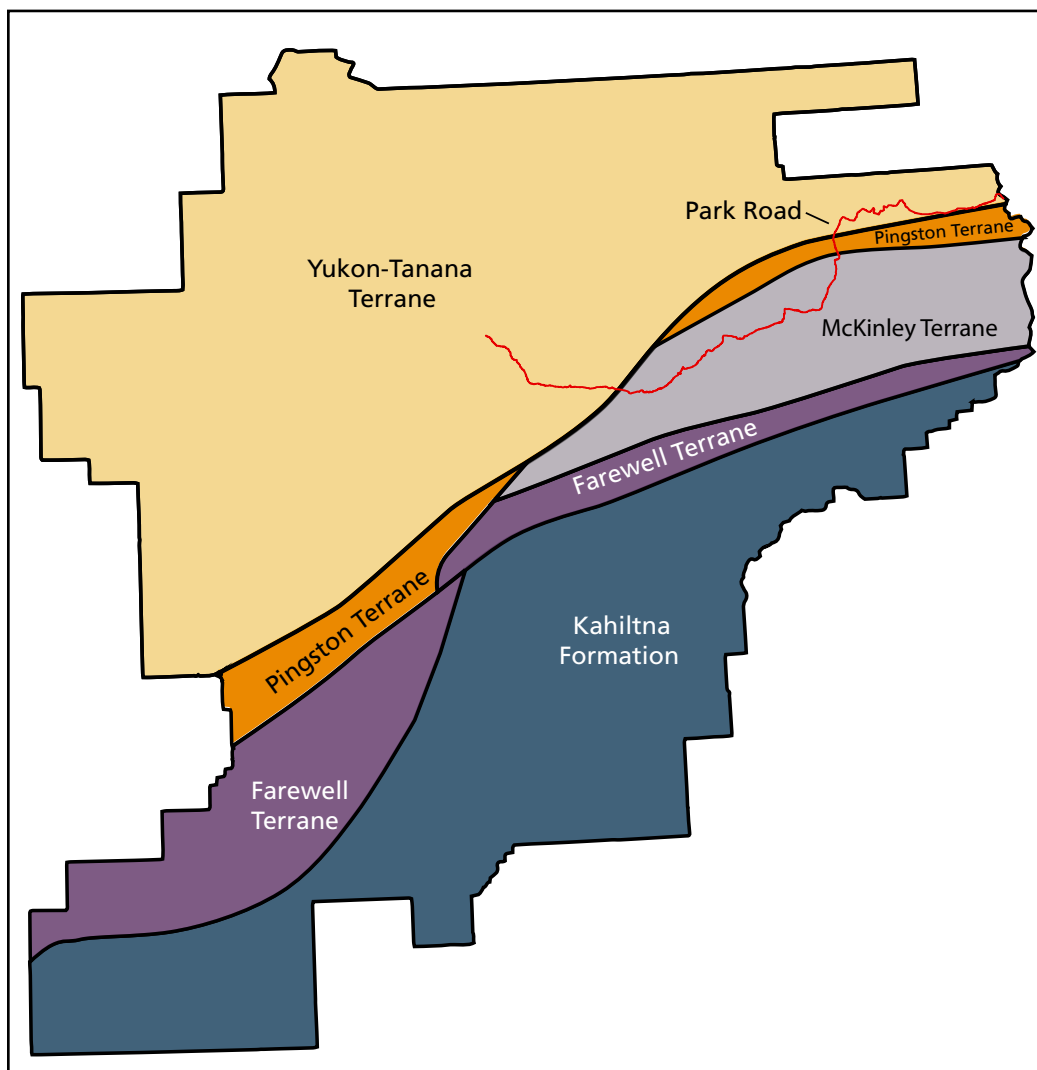


Above: Map of significant terranes, formations, and sediments of the south-central part of Alaska. Boundary of Denali is denoted by a white line^{69, 70}.

the Yakutat Plate against southern Alaska³⁰. This process can be seen in places like Wrangell-St. Elias National Park and Preserve, where the Yakutat Terrane is currently accreting onto the North American Plate at a rate of about two inches (five cm) per year⁵³.

Denali contains four extensive terranes, several smaller ones, and a large sequence of rocks called the Kahiltna Flysch. From the park entrance west to about the Teklanika River, the park road follows the Hines Creek Fault along the boundary between the

Yukon-Tanana Terrane to the north and the Pingston Terrane to the south. From approximately Mile 26 west to Mile 72, the road continues through the Pingston and McKinley terranes. These terranes are mostly buried by younger formations such as the Cantwell and Teklanika, which were deposited and erupted, respectively, on top. Near the terminus of the Muldrow Glacier, the park road again crosses the Hines Creek Fault and reunites with the Yukon-Tanana Terrane. While often buried by sediments, the Yukon-Tanana is visible again west of Wonder Lake. Farther south, the Kahiltna Formation is separated from the Farewell Terrane by the McKinley Strand of the Denali Fault in the east and the Shellabarger Fault in the west. However, neither the Farewell Terrane nor the Kahiltna Formation is crossed by or easily visible from the road^{9,69}.



Left: Map of approximate locations of extensive terranes and formations within Denali National Park and Preserve⁹.

MILE Teklanika River and 30.2 Surrounding Area

The rest stop here overlooks the large, braided Teklanika River where wildlife often roams. Having left behind the Hines Creek Fault and the metamorphosed Yukon-Tanana Terrane just a few miles back, you will begin crossing through a dynamic mix of sedimentary and igneous rocks. Both Cathedral and Igloo mountains, which flank the road up ahead to the east and west respectively, are composed of the Cantwell Formation, a thick bed of sedimentary rocks that is topped and intruded by the colorful volcanics of the Teklanika Formation.

Archaeological sites in the area contain materials composed of local and distant rock sources. For example, chert was collected near this location, while obsidian was likely sourced from upstream exposures of the Teklanika Formation³⁹. Obsidian and chert were used for over 13,000 years by inhabitants of this area to make projectile points, scrapers, and other tools. These tools were used to hunt bison, caribou, and other animals.

The Cantwell and Teklanika formations were originally considered one formation, with the older

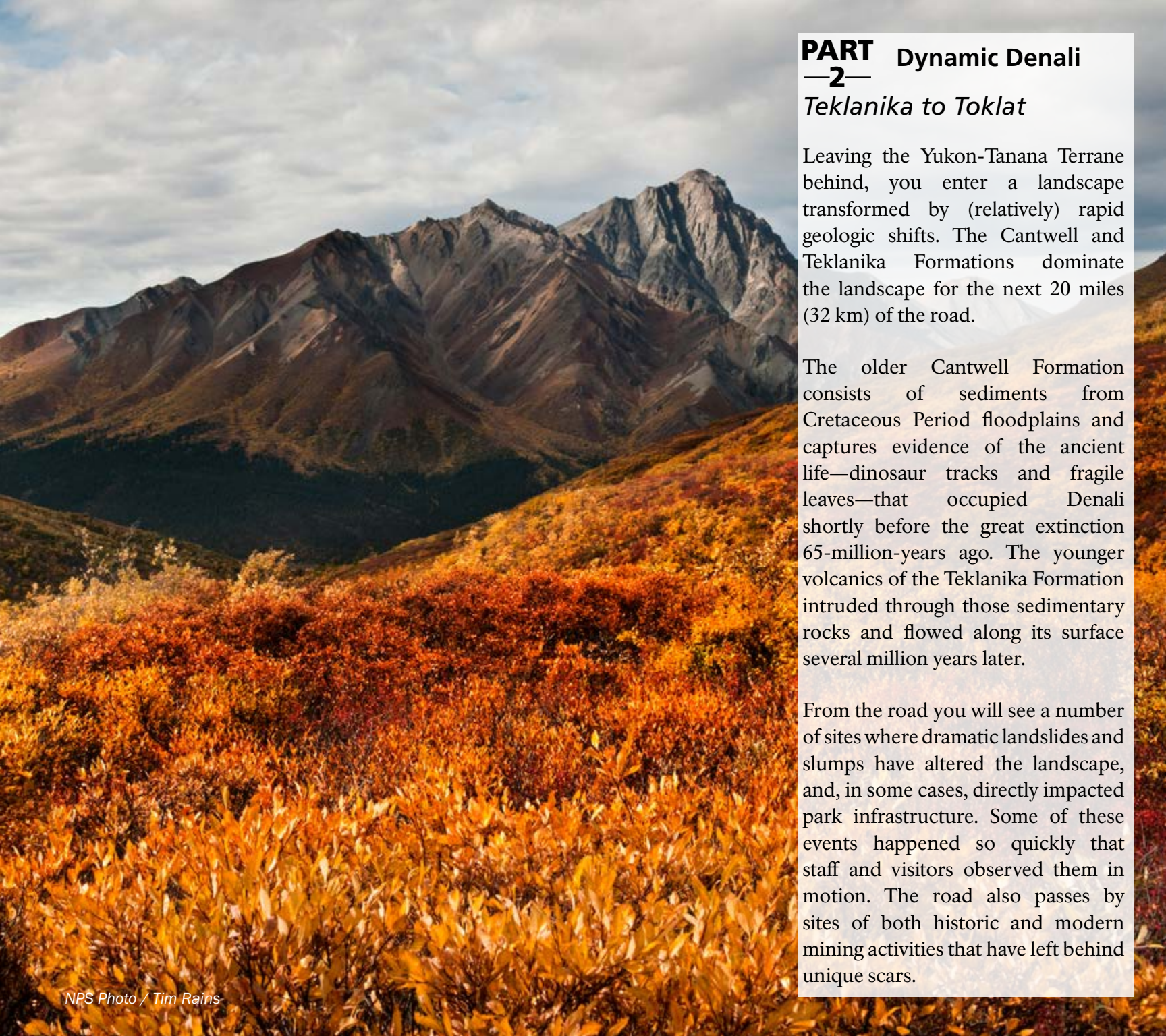
sedimentary layer called the Lower Cantwell and the younger volcanic layer called the Upper Cantwell. However, the different geologic compositions and ages of the two formations warranted the use of two different names^{20,41}.

Below: The braids of the Teklanika River flow framed by mountain peaks.

Opposite Page: The colorful Polychrome Mountain area is an excellent place to look for interesting geologic features.



NPS Photo / Alex Vanderstuyf



PART **—2—** **Dynamic Denali** *Teklanika to Toklat*

Leaving the Yukon-Tanana Terrane behind, you enter a landscape transformed by (relatively) rapid geologic shifts. The Cantwell and Teklanika Formations dominate the landscape for the next 20 miles (32 km) of the road.

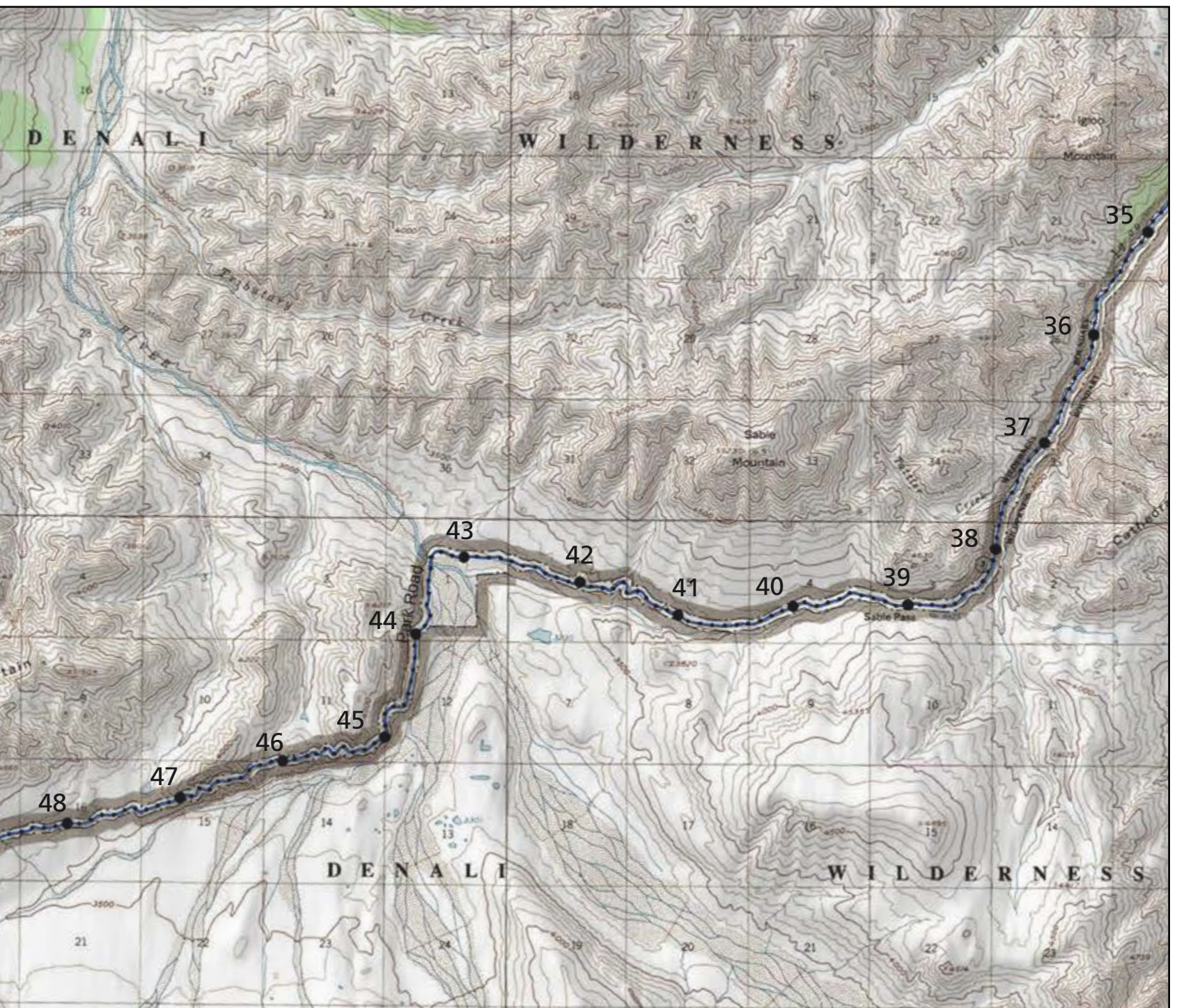
The older Cantwell Formation consists of sediments from Cretaceous Period floodplains and captures evidence of the ancient life—dinosaur tracks and fragile leaves—that occupied Denali shortly before the great extinction 65-million-years ago. The younger volcanics of the Teklanika Formation intruded through those sedimentary rocks and flowed along its surface several million years later.

From the road you will see a number of sites where dramatic landslides and slumps have altered the landscape, and, in some cases, directly impacted park infrastructure. Some of these events happened so quickly that staff and visitors observed them in motion. The road also passes by sites of both historic and modern mining activities that have left behind unique scars.

Mile Feature

35.3	Teklanika and Cantwell Formations Meet
35.6	Teklanika Dikes
36.9	First Dinosaur Footprint Found in Denali
37.5	Tattler Creek
37.7	Igloo Debris Slide
41.1	Sable Pass Landslide
42.5	Coal Mining by the East Fork Toklat
43-47	Polychrome Pass
44.9	Bear Cave Slump
45.4	Building the Park Road
45.4	Pretty Rocks Landslide
45.7	Spheroidal Weathering
45.8	Polychrome Overlook —Looking South
45.8	Polychrome Overlook —Looking North
47.6	Effects of Permafrost Thaw
48–50	Patterned Ground
49.9	Road Blocking Debris Flow
53	Toklat River





MILE Teklanika and Cantwell 35.3 Formations Meet

As you pass between Cathedral and Igloo mountains to the south and north, respectively, keep an eye out for color changes in the nearby outcrops. The base rock is the Cantwell Formation, typically colored gray but often covered with vegetation. Above it is the Teklanika Formation, which is younger and generally characterized by reddish- or yellow-brown-colored rocks. These two formations represent a very active time in Denali's history, and their existence heavily influences the local topography and the difficulty of road maintenance.

The Cantwell and Teklanika Formations were born of sedimentation and volcanism, respectively. Around 80 million years ago, plate tectonics crumpled this area and created the Cantwell Basin. Over the next 10 million years, nearly 2.5 miles (4 km) of cobbles, gravel, sand, and silt filled in this basin. The sediments solidified over time into the sedimentary rock now referred to as the Cantwell Formation. Then around 60 million years ago during the Paleocene Epoch, lavas began to intrude the Cantwell Formation, forming the dikes, sills, and lava flows of the Teklanika Formation. Over the next 5 million years, nearly 2 miles (~3 km)

of volcanic rock accumulated on top of the Cantwell Formation, primarily as alternating layers of basalt-andesite and rhyolite lava each several hundred feet

thick. The lavas are interspersed with pyroclastic flows and other materials ejected from volcanoes²¹.



NPS Photo / Lian Law

Above - The ~55 million-year-old igneous Teklanika Formation rocks vary in color from yellow to red to brown, among others.



NPS Photo

Above - The ~70 million-year-old sedimentary Cantwell Formation rocks are usually gray in color.

MILE Teklanika Dikes

35.6 Several intrusions of the igneous Teklanika Formation through the sedimentary Cantwell Formation can be seen on the northwestern side of the road here. They appear as dark orangey-brown bands—dikes of cooled magma—cutting through the gray outcrop from the lower left to the upper right.



G E O Paleontological **FEATURE** Wonders

The Cantwell Formation is a wonderland for anyone who likes to search for and observe fossils in their natural settings. Fossils from the Cantwell Formation were deposited ~70 million years ago during the Late Cretaceous Period³⁷. This was just prior to the Cretaceous-Paleogene mass extinction that wiped out dinosaurs around 65 million years ago.

The abundance and quality of the fossils found in Denali National Park and Preserve makes it a world-class site for tracks of dinosaurs and other animals that lived in Alaska during the Cretaceous Period. Tens if not hundreds of thousands of fossil footprints from this period are estimated to be preserved in the park. Most fossils that have been found to date are located in the Sable Mountain and Polychrome Pass areas. One site has so many thousands of dinosaur tracks packed into an area barely larger than a football field that people refer to it as a dinosaur dance floor!

The first dinosaur footprint in Denali was found in 2005⁵⁴. Since then thousands of footprints have been discovered and catalogued. The most abundant fossil tracks by far were made by hadrosaurs, which

were enormous (up to ~30 feet / 10 m long) herbivores that lived in herds. Tracks left by theropods (cunning carnivores), ceratopsians (beaked and horned herbivores), pterosaurs (flying reptiles), and birds have also been discovered.

In 2016, researchers discovered the first dinosaur bone in the park – a small fragment of ossified tendon from a hadrosaur²⁸. As of 2020 about ten dinosaur bones, mostly fragments, have been found in Denali. The biggest bone found to date is a 20 inch (50 cm)

long hadrosaur rib, but researchers expect to find many more in future years.

In 2018, a graduate student found a significant new theropod track at a site near the Toklat River. The track is so large – 20 inches (50 cm) long and almost equally wide – that it would barely fit inside of a typical bicycle wheel! Based on the relationships between foot length and hip height, the animal that made the print was at least seven feet (2 m) tall at the hips. The only group of theropods known

Below: Hamamelidaceae family (witch hazel) leaf fossils from the Cretaceous Cantwell Formation.



from North America during the Late Cretaceous that was big enough to create such a print are tyrannosaurs. This is the first evidence of such large tyrannosaurs living in Alaska and the largest known terrestrial predator in Alaska's history. The finding challenges the notion that only a diminutive species of tyrannosaur was present in Alaska in the Late Cretaceous³⁵.

Along with footprints and bones, other types of animal fossils that have been found in the Cantwell Formation include scaly skin impressions, linear tail drags, coprolites (fossilized dinosaur dung), leaves that were trampled by dinosaurs, and invertebrate trace fossils. There is even evidence of family groups traveling together, with family members ranging in size from juveniles to adults³⁵.

Thousands of fossilized leaves, wood fragments, and cones have been discovered within the Cantwell Formation. Analyses of these plant fossils indicate that 70 million years ago Denali's climate was cool and temperate with distinct seasons. The dinosaurs and other animals would have lived through short, warm, dry summers and long, comparatively mild, and probably wet winters⁷⁴. This



Above: An exemplary track of an ornithopod, likely a hadrosaur from Tattler Creek.

mild climatic regime is substantially different from that of modern interior Alaska.

However, almost identical to today, there would have been nearly 24 hours of sunlight in

mid-summer and the opposite in mid-winter because Alaska was at a similar latitude then as now⁵⁸. Scientists look for evidence of how dinosaurs and plants adapted to snow and long periods of darkness as they study subarctic fossils.

MILE First Dinosaur Footprint 36.9 Found in Denali

Denali's first evidence of dinosaurs—a single theropod footprint—was discovered here by a University of Alaska Fairbanks geology student in the summer of 2005. On that fateful day, a small group of students on a geology field trip was examining the Cantwell Formation outcrop that you can see just on the other side of Igloo Creek. The professor told the group that the Cantwell rocks were the right age and paleoenvironment to preserve dinosaur fossils, but that none had yet been found in the park, not even tracks. One attentive student asked what such fossils would look like, and, following the description, promptly pointed to a three-lobed blob on the rock nearby and asked, "Like this one?"⁵⁴

If you stop by the Murie Science and Learning Center in the entrance area of the park, you can see this original footprint and other fossils up close in the Cretaceous Denali exhibit.

Right - This theropod track is the first dinosaur fossil found in Denali. If you find a fossil while hiking in the park, please remember to leave it for others to enjoy.





Photo by Pat Druckenmiller

Above: You need to look closely to differentiate the tracks from the rest of the outcrop.



Alaska Geographic Photo

Above: This hadrosaur footprint from the Tattler Creek area has one broken toe.

MILE Tattler Creek

37.5 A few-mile hike up Tattler Creek brings you to one of Denali's best areas for viewing dinosaur tracks from the Late Cretaceous (~70 million years ago). In the Tattler drainage there are thousands of dinosaur and plant fossils. The plant fossils show that the dinosaurs were walking through a forest where large conifers towered above small deciduous trees, with ferns, cycads, and horsetails growing in the understory⁷⁴. Fossils found in this drainage include footprints left behind by hadrosaurs, theropods³⁴, pterosaurs³⁷, and several types of birds³⁶.

FUN FACT: The Cantwell Formation has among the highest bird fossil diversity of any formation in the world. One charismatic bird that formerly soared above Denali was *Magnoavipes denaliensis*, an ichnospecies (species known by tracks only) new to science that was first discovered in Denali in 2008³⁶. This large, crane-like bird with eight-inch (20 cm) diameter tracks is among the few species that have been named in honor of Denali.



Photo by Jan Tomsen

Above: The earth is alive in Denali! Hikers often find areas of the landscape that show signs of movement that are likely associated with permafrost thaw.

G E O Precarious FEATURE Permafrost

Glaciers aren't the only frozen forces altering landscapes in Denali. Permafrost – soil or rock that is continuously frozen for at least two years – presently underlies approximately 50% of the park at shallow depths⁵⁹. Throughout the park permafrost coverage varies between continuous (>90% frozen), discontinuous (50-90% frozen), sporadic (0-50% frozen), and absent.

Unsurprisingly, the extent of permafrost in Denali is changing as the climate warms. The average annual temperature throughout much of Denali is just below freezing, so recent trends towards years with average annual temperatures that are 3 – 5 °F (1 – 3 °C) above normal means that some soils are crossing above the freezing threshold of 32 °F (0 °C)⁷¹. Thawing permafrost is the inevitable result.

Scientists have created permafrost models that incorporated data from soil surveys, vegetation cover maps, and climate models of hindcasted and forecasted ground temperatures. The results indicated that during the 1950s the park was approximately 75% underlain by shallow permafrost, while by the 2050s this number will have decreased to only 6%⁵⁹.

We are already seeing evidence of permafrost thaw predictions coming true in the form of increased landslide activity throughout the park. While landslides are exciting to ogle from a distance, they become issues wherever they intersect the Denali Park Road. Over 140 unstable slopes that pose risks to humans and infrastructure have been identified along the entire 92-mile park road, with two of the most significant being located in Polychrome Pass¹⁹. Permafrost has been identified in association with many of the unstable slopes along the park road through monitoring

wells, surface landscape features, and slide-induced exposures. Although long-term permafrost monitoring has not been conducted in Denali, the increasing number, size, and velocity of landslides in the park is consistent with regional trends in permafrost thaw⁷¹.

Another distinct example of permafrost thaw is just out of sight to the north of the road at Mile 47.6. USGS geologist Stephen R. Capps photographed the area in 1916, and then researcher Ron Karpilo repeated the photos in 2011. The photo pair shows that permafrost thaw beneath and around the lakes

over the last century likely caused some of them to drain. At the same time, new lakes formed nearby where ice loss caused the land to subside into closed depressions⁶⁴. This phenomenon is occurring on a large scale in the vast lowlands that dominate the northwestern part of the park. In that area, 19% of the lakes drained, 26% shrank markedly, and 11% expanded between 1980 and 2007⁵¹.

Below: Repeat photography of lake changes likely caused by thawing permafrost. Note that between 1916 and 2011 the large lake mostly drained, new small lakes formed, glaciers in the background retreated, and vegetation changed from predominantly lichens to shrubs⁶⁴.



MILE Igloo Creek Debris Slide

37.7 In late October 2013, the hillside above you failed catastrophically, creating a 600-foot-long (185 m), 110-foot-wide (35 m) debris slide that buried the park road. The debris consisted of blocks of permafrost-rich, unconsolidated soil and rock as thick as 17 feet (5 m) and as large as small cabins. It took four days and nights for the park's maintenance staff to bulldoze the road clear. Safety monitoring and maintenance will continue indefinitely.

Why does a debris slide suddenly release from a slope that has been fairly stable for decades? Geologists and engineers determined that the slope failed because the debris slid on a steep, slippery, unfrozen clay layer. The clay was originally deposited as a layer of volcanic ash within the Teklanika Formation 55-60 million years ago, and subsequently weathered into clay.

However, the trigger—in other words what initiated the debris to slide on that particular day—remains unknown. One leading hypothesis is that forces associated with the expansion of ice during repeated freeze-thaw cycles served as the trigger. Ground, aerial, and satellite images and road maintenance staff observations indicate that a small slide and other precursor

events occurred here in the late 1980s, as well as in the months before the 2013 event. We also know in hindsight that groundwater was seen seeping from the area in the months prior to the slide and that the ground was beginning to move slightly. In the days preceding the slide, the area experienced temperatures that fluctuated near freezing, making it plausible that ice expansion might have pushed the clay layer to the point of failure, allowing it to slide.

Thus freeze-thaw dynamics were likely a trigger for this landslide, but freeze-thaw cycles happen every year in Denali, leaving open the question of why this major slide occurred in 2013. One hypothesis is that climate change-induced permafrost thawing is to blame. While specific permafrost-degradation trends are presently unknown in Denali, thawing would be consistent with regional trends recorded by researchers in recent



NPS Photo / Denny Capps

decades^{58,68}. It is possible that the permafrost thinned through the clay layer over many years, and that in 2013 the clay finally thawed enough for the slide to occur.

Studies are in progress to understand the causes and possible mitigation of debris slides and other geohazards all along the park road. The same, or similar, ~55-million-year-old clay layer in the Teklanika Formation occurs frequently along the road corridor. Several of these locations have already experienced slumps and slides that have undermined or blocked the road. National Park Service and Federal Highway Administration staff continuously monitor known hazardous locations and assess the risk of future slides.

Opposite Page: A geologist examines a 17-foot-thick block of frozen debris that slid during the October 2013 event. The soil and rock fragments were held together by permafrost. The geologist is standing on the failure plane of the slump, a slippery layer of ~55-million-year-old volcanic ash that weathered into clay.

Right: Two geologists (in the red circle) examine the debris slide. The park road is denoted by a dashed red line.



NPS Photo / Denny Capps

MILE Sable Pass Debris Slide

41.1 In a matter of days, what started off as a fracture line in the tundra to the south of the road became a massive movement of sediment and vegetation. On June 12, 2009, ~22,000 cubic yards (17,000 m³) of material in the form of blocks of tundra and underlying gravels and sand slumped 30–40 feet (9–12 m) downslope¹². Since then, the once tabular slumped blocks have become pyramidal due to thaw and erosion, and the formerly undercut headwall from which the blocks broke away has become rounded.

The sudden slide was likely caused by two known slow processes and an unknown trigger. The first process was that the slope of the poorly-consolidated, lighter-colored sandstones of the Usibelli Group (5–23 million years old) and the more recent, darker-colored glacial or fluvial sediments (>10,000 years old) was undercut by the stream below. The second was that permafrost thaw likely destabilized the slope by adding water and removing internal cohesion¹².

Right: Photo of the Sable Pass Debris Slide a week after it occurred. Note the large blocks of poorly consolidated sediment held together by permafrost.

This slide has interesting similarities and contrasts to the Igloo Debris Slide. They both were composed primarily of water-saturated sediment and sediment and blocks frozen together by permafrost. However, the two slides occurred in dissimilar rock formations—the Igloo slide in volcanic

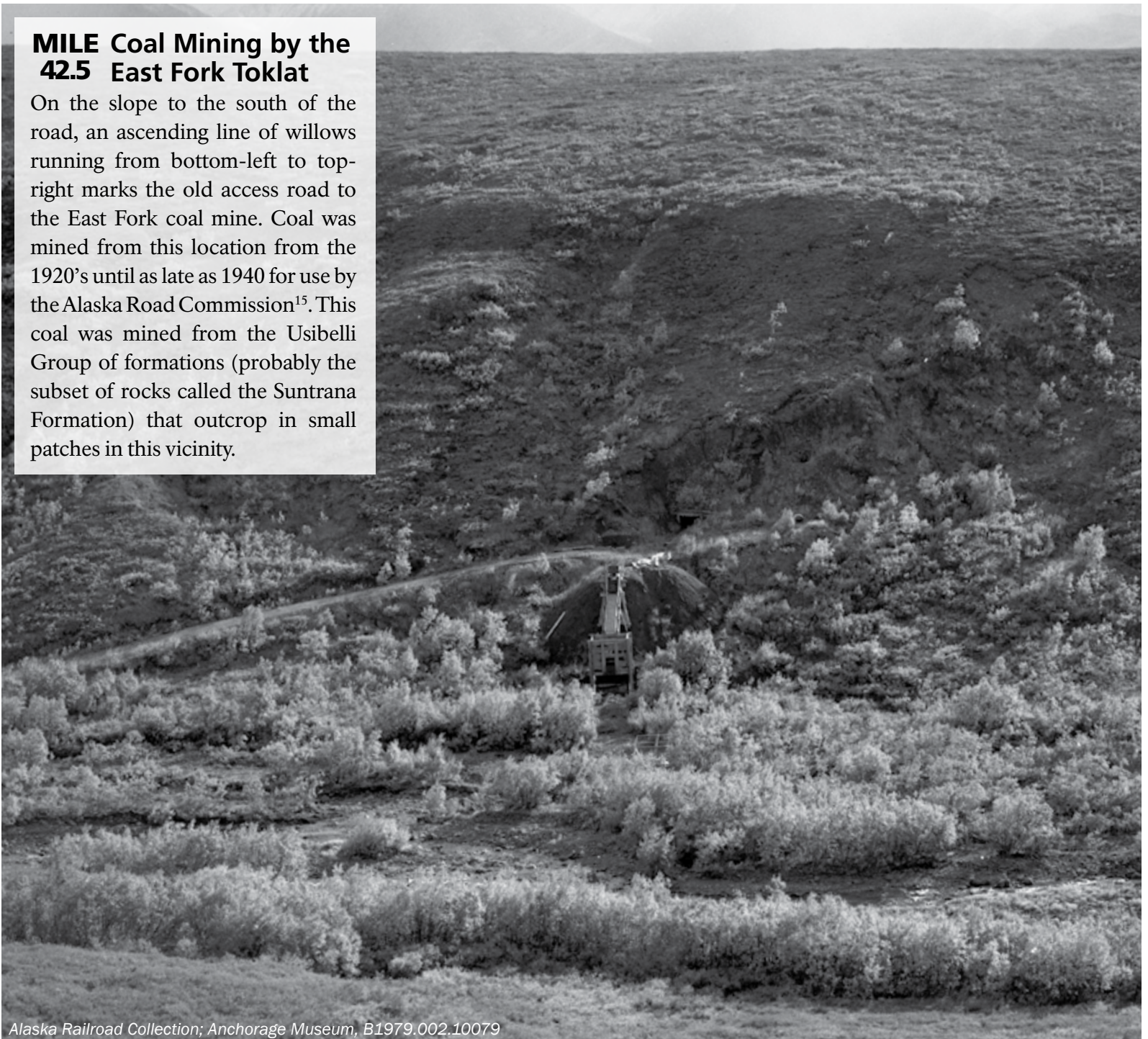
rocks and the Sable slide in younger sedimentary rocks and deposits. In addition, the Igloo slide had a well-defined failure plane composed of clay, while the Sable slide failure plane appeared to be composed of similar material to that of the slide.



NPS Photo

MILE Coal Mining by the 42.5 East Fork Toklat

On the slope to the south of the road, an ascending line of willows running from bottom-left to top-right marks the old access road to the East Fork coal mine. Coal was mined from this location from the 1920's until as late as 1940 for use by the Alaska Road Commission¹⁵. This coal was mined from the Usibelli Group of formations (probably the subset of rocks called the Suntrana Formation) that outcrop in small patches in this vicinity.



MILE Polychrome Pass

43-47 The next four miles of road traverse a steep slope high on the side of Polychrome Mountain. Named for its wide range of vibrantly-colored rocks, Polychrome Mountain is comprised of volcanic rock of the Teklanika Formation which erupted and cooled quickly on the Earth's surface around 55-60 million years ago. Generally, the lighter volcanic rock of the Teklanika Formation is rhyolite and the darker rock is basalt. Within those rock types, relatively small changes in rock chemistry result in the bright pallet of chromatic variety before you. For example, small changes in the percentage of the element iron can cause rocks to be black, blue, green, yellow, or orange, with the hues growing more vibrant as the iron oxidizes.

Polychrome Pass is memorable for its vivid rock colors and breathtaking vistas, but from a geological perspective it possesses intrinsic hazards. The Teklanika Formation is no exception to the general rule that volcanic rock is crumbly and weak and thus prone to landslides. The area is also rich with permafrost. Increased temperatures and rainfall (both amount and severity) associated with climate change are believed to be causing the permafrost to thaw, resulting in slope failures⁷¹. This is due to reduced cohesion and increased

pore pressure between grains. The park road bisects these landslides as it winds along the Polychrome cliffs, creating massive and ongoing infrastructure challenges. Descriptions of the most significant Polychrome landslides are provided in the following pages.

The Denali Park Road offers treasured access into Alaska's wildlands for hundreds of thousands of visitors per year, but the landslides are jeopardizing

that opportunity. What is the solution? That is an exciting question that the park is working hard to answer. The National Park Service, the Federal Highways Administration, and other partners are considering fixes that range from minor improvements within the existing road alignment to multi-mile reroutes. Unfortunately there is no simple answer. Steep slopes above and below limit the potential for reroutes adjacent to the current road. Bridges,

Below: Park visitors enjoy the views from Polychrome Overlook.



NPS Photo / Lucy Chang

deep patches, and earthwork are being considered. Reroutes are feasible, but would require building 6+ miles of new roadway through federally designated wilderness. Numerous long bridges across braided river floodplains would be needed, and there would be significant challenges associated with constructing and maintaining a road on glaciated uplands that are underlain by ice-rich permafrost.

It is worth noting that considerable thought and money went into the early 1920s decision to opt for the high Polychrome Pass road alignment rather than having the road wind across the braided river floodplain below⁵⁰. The decision to build the “High Line” was foremost born of the desires to create “one of the most scenic highways in the National Park system,” with the added advantage of avoiding the need for

bridges. It was arguably an extremely successful decision, providing millions of visitors with unparalleled vistas for the last 80+ years. Ensuring safe and similarly inspiring access into the heart of Denali for the park’s second century of visitors is the park’s highest priority.

Below: A bus navigates the colorful curves of Polychrome Pass.



NPS Photo / Kent Miller

MILE Bear Cave Slump

44.9 A tight turn of the road here skirts a large, continuously-moving slump easily seen below and ending where a tributary to the East Fork River erodes its terminus. Because of the threat it poses to the park road, this landslide has been carefully monitored since 1993¹⁰. Like the Igloo Debris Slide near Mile 38, this slump is composed of unconsolidated sediments from the Teklanika Formation, including a slippery clay layer of altered volcanic

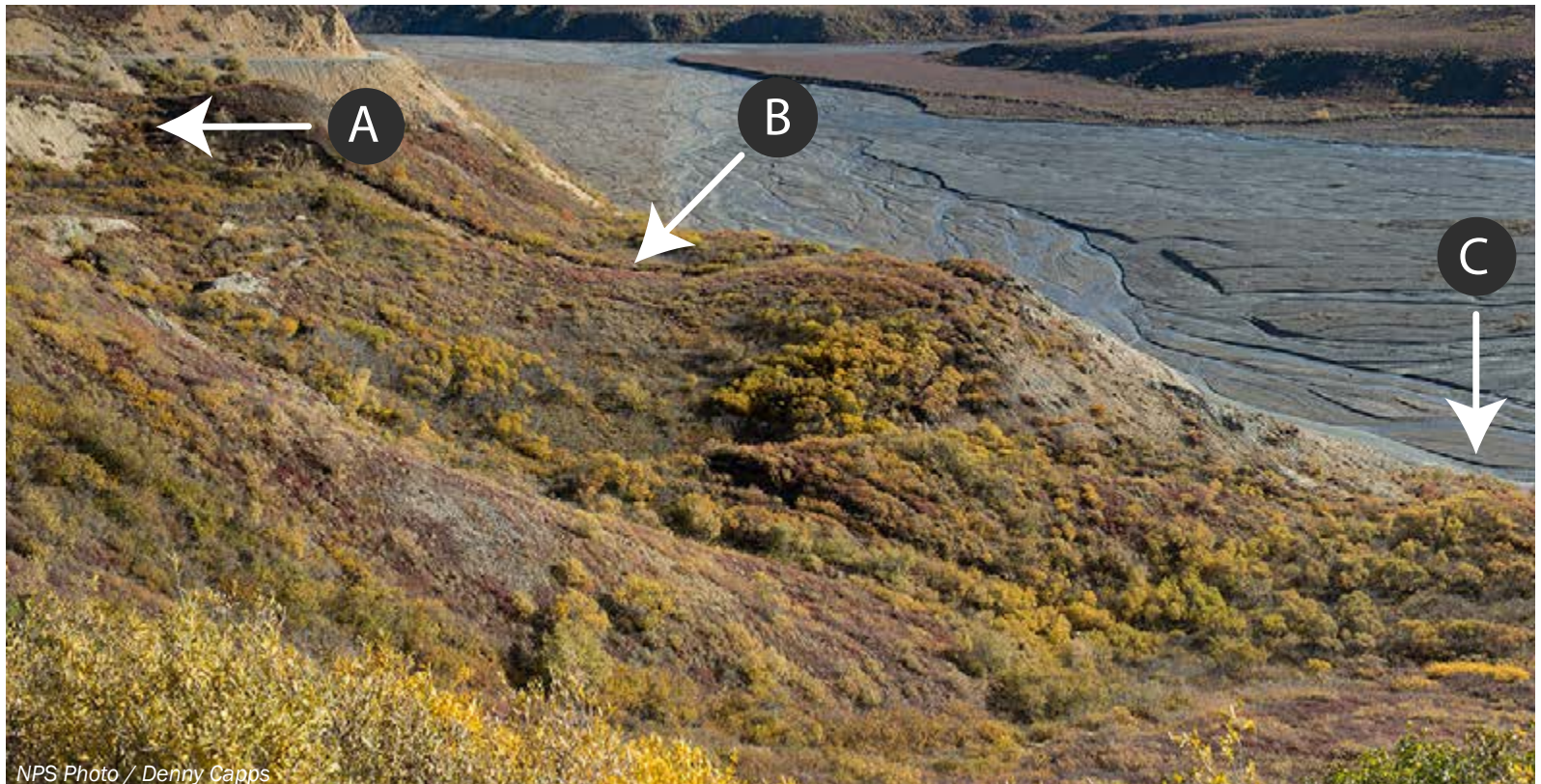
ash that contributes to its movement. The small 'bear cave' on the slope above, for which the slump is named, may be a prospecting pit from the early 1900s or a natural feature.

Monitoring by traditional and GPS surveying techniques has demonstrated that the slump moves faster in years with higher rainfall. Between 1993 and 1994, part of the slide moved 8.4 feet (2.6 m). In 1999, a project to divert

surface water away from the area succeeded in significantly reducing the slump's movement¹⁰. Subsequent annual resurveys indicate that downward motion has slowed to about 3 inches (8 cm) per year on average.

The pipes that you may notice sticking out of the ground on the slump are used to monitor ground water levels and the changing angle of the slump.

Below: View of the Bear Cave Slump showing the main scarp (A) just below the road in the upper left, the minor (or lateral) scarp (B) near the center, and the terminus (C) to the right where it is eroded by a tributary to the East Fork River below.



NPS Photo / Denny Capps

MILE Building the 45.4 Park Road

The 90-mile (now 92) long Denali Park Road was built between 1922 and 1938 by the Alaska Road Commission. Along with facing cold weather conditions and short seasons, the construction crews had to overcome interesting challenges associated with the park's rugged and unstable terrain. In some locations such as Polychrome Pass, the crews painstakingly blasted out a road corridor high on the steep hillsides to maximize scenic vistas. In other locations, they were forced to grade and re-grade "completed" road sections that shifted and sank as the newly-disturbed permafrost thawed underneath¹⁵. These and other challenges of working in the remote subarctic are still faced by Denali's road crews today.

Photo: An early park bus going over the "High Line" section of the Park Road now called Polychrome Pass.

DENA 2262, DNP&P Museum Collection



MILE Pretty Rocks

45.4 Landslide

A sharp right-hand turn in the road with breathtaking drop-offs to the left brings you to Pretty Rocks Landslide. Park managers have been aware of this landslide since the 1960s, but it wasn't considered a major issue until it began to speed up markedly in 2014. By 2018 the slide rate had increased to as much as 13 inches per month, creating a swale that steepened the road gradient and limited sight lines. Beginning in August of 2019 and continuing until the time of this writing in January 2020, Pretty Rocks Landslide is moving downhill at a rate of almost 60 inches (1.5 m) per month with approximately 300 feet (91 meters) of the Denali Park Road in its clutches. Unfortunately there is no easy bypass.

Why is Pretty Rocks Landslide changing so quickly, and why now? Boreholes drilled into the road between 2003 and 2019 have revealed significant amounts thaw-sensitive (relatively warm) ice-rich permafrost directly beneath the road. Thus the most plausible answer is that the permafrost in the area is thawing, consistent with regional trends, resulting in loss of slope stability⁷¹. Recent increases in precipitation amount and severity are probably contributing as well.

The National Park Service is collaborating with the Federal Highways Administration on short- and long-term solutions to the changing road dynamics at Pretty Rocks. Options currently under consideration include a bridge, earthwork, or a significant reroute. See Mile 43 – 47 Polychrome Pass for additional information.

Below: An aerial view of the Pretty Rocks Landslide, taken on December 18, 2019. Note the slumping along the 300-foot-long section of the Park Road. Orange and yellow lines indicate eastern and western landslide scarps, respectively. The largest drop is seen on the eastern side (see close-up photo on opposite page). Two park employees (circled in red) can be seen on the road surface to the left of the western scarp for scale.





Above: Approximate outline of the active landslide at Pretty Rocks.

Left: Park geologist standing on the eastern scarp of Pretty Rocks Landslide on January 2, 2020. He is standing on the dropped portion of the road bed and pointing to where it had been connected as of September 25, 2019. The vertical offset between the two points in January 2020 was 15 feet.



MILE 45.7 Spheroidal Weathering

Spheroidal weathering is a type of chemical and physical weathering that rounds jointed rock surfaces as water runs along cracks in the rock. While this outcrop is made of volcanic rocks from the Teklanika Formation, these features should not be confused with pillow basalt, which is a volcanic rock that forms underwater. You can see pillow basalt along the road at Mile 67.5.

MILE Polychrome Overlook 45.8 —Looking North

An arcing light-green layer of clay has stained the rocks below it on the north side of Polychrome Overlook. This clay is the product of volcanic ash weathering over time.

Beginning in 2002, a layer of this slippery clay at the overlook caused half of the road to slump over four feet (~1.5 m) during several episodes of heavy precipitation⁷⁶. To mitigate the slumping, Federal Highways

Administration and park staff removed the clay, backfilled with materials that were less susceptible to slumping, and added perforated pipes to drain water from the area⁷⁶. The pipes have no obvious inlets, but their outlets can be seen poking out of the slope on the south side of the road.

Note that this is the fourth location described in this guide where clay in the Teklanika Formation has caused

a slump or slide that has buried or undermined the park road (Mile 37.7 Igloo Debris Slide, Mile 44.9 Bear Cave Slump, Mile 45.5 Pretty Rocks Landslide). Unfortunately for park managers, there are several additional locations where the road is vulnerable due to similar clay layers.

Below: An outcrop of unstable clay arcs north of the road at Polychrome Overlook.



NPS Photo





MILE Polychrome Overlook 45.8 —Looking South

If you're a fan of geology, this is a great place to get out and walk around! A number of interesting glacial features can be seen from the Polychrome Overlook. High in the valleys to the south are the Polychrome Glaciers, barely visible as white patches of ice flowing towards the park road. Each of these glaciers terminates in a dark, stagnant, debris-covered ice field. The Polychrome Glaciers have retreated and downwasted substantially since they were first documented⁶⁴, and will likely disappear completely in the coming decades if the climate continues to warm.

Between the glaciers and the road is a large outwash plain referred to as the Plains of Murie after famous wildlife biologist Adolph Murie. On days with clear skies, kettle ponds, mostly located towards the east end of this expanse, shine brightly on the plains. Overcast days more easily reveal solifluction lobes on some of the lower mountains. These lobes look like dripping paint from far away, and indeed they are dripping in a sense, as they are caused by the slow, downslope creep of water-saturated soils and sediments. Solifluction lobes are common in areas with permafrost and can be seen on hillsides throughout the park.

FUN FACT: A 35-foot-high (11m), house-sized erratic boulder on the lowlands to the south, transported to its current location by glaciers in the Pleistocene Epoch, looks small upon the vast Plains of Murie.

See if you can find the house-sized erratic (pictured below) on the vast Plains of Murie (pictured on opposite page).



NPS Photo



NPS Photo / Emily Mesner

Above: The Denali Park Road winds along the edge of Polychrome Mountain, providing excellent views, but challenging terrain.

MILE Patterned Ground

48-50 Permafrost landscapes are sometimes identified by surficial signatures such as patterned ground features, which commonly appear in the form of stripes, circles, and polygons. Just out of sight approximately 0.75 miles (1.2 km) south of the road are intricately patterned geometric shapes called

ice wedge polygons. Ice wedges form when the ground cracks due to contraction from cold and then water later fills the cracks, freezes, and expands. The cycle repeats annually, growing the ice wedges and jacking open the cracks. Sometimes multiple ice wedges join together to create ice wedge polygons.

Where soil is homogeneous, these polygons may appear hexagonal²⁴. At this location the soil is heterogeneous, which causes the pattern to be rather irregular.

Below: 2004/2005 IKONOS satellite image of ice wedge polygons 0.75 miles south of Mile 49.



G E O **Glaciers**

FEATURE Glaciers are powerful forces of nature that have molded Denali's landscape in the past and continue to do so today. Lobes of ice have flowed down from the high peaks of the Alaska Range into the lowlands during several glacial cycles over the past two million years.

Glaciers leave behind many signs of their passage. As a glacier flows, it grinds away and breaks off rocks underneath. This debris, along with rock material that falls onto the glacier's surface, gets pushed to the edges of the ice and left behind as

lateral moraines along the sides and terminal moraines at the end. The park road crosses several moraines from the last ice age, but few are obvious from the ground. However, the road runs along an enormous lateral moraine from Mile 75–84 that was formed from repeated expansions of the Muldrow Glacier over 10,000 years ago.

Glaciers also carry boulders, known as erratics, to new locations far from their sources. Good places to spot erratics in Denali include Park Headquarters (Mile 3.4) and Polychrome Overlook (Mile 45.8).

FUN FACT: Like much of interior Alaska, the northern portion of Denali National Park and Preserve persisted unglaciated during the last ice age. Even though the area was very cold, the northern side of the Alaska Range was too dry to support extensive ice sheets like those that covered the south side of the range. During this time, Pleistocene animals such as giant bison and woolly mammoths roamed the steppe tundra in an area known as Beringia. Beringia encompassed Alaska, eastern Siberia, and the land bridge in between⁴².



NPS Photo / Kent Miller

Glacial transformation of Denali's landscape isn't restricted to the materials that frozen rivers leave behind. Glacial scouring creates broad, gently curving U-shaped valleys, in contrast to the V-shaped valleys eroded by moving water as seen at Savage River (Mile 14.7). Ice converging at the tops of valleys from many sides speeds up its flow, carving out deep, curved amphitheaters, called cirques, like those visible from Polychrome Overlook (Mile 45.8). Kettle ponds dot the landscape below Polychrome Overlook, around the Teklanika rest stop (Mile 30), and near Wonder Lake (Mile 74-86).

Glaciers currently cover approximately 15% of Denali National Park and Preserve. Comparing recent satellite images to maps created in the 1950s, geoscientists have determined that Denali's glaciers have retreated 8% in extent and lost 30 cubic miles (126 km³) of volume over the last sixty years⁴. Repeat photographs provide

Opposite Page: Great Gorge of the Ruth Glacier as viewed from the air on the south side of the Alaska Range.

Right: Repeat photographs of the easternmost Teklanika glacier. The glacier has retreated approximately 450 yards (410 m) and downwasted approximately 300 feet (90 m) between 1959 and 2010⁶⁴.

vivid visual evidence that Denali's glaciers have downwasted (surface elevation decreased) and retreated substantially over the past century. An early geologist with the U.S. Geological Survey, Stephen Reid Capps, took

many photos in the park in the early 1900s. Since that time many of his photos have been repeated to capture evidence of glacial retreat as well as other landscape changes.





NPS Photo / Riley Tingue

MILE 49.9 Road-Blocking Debris Flows

Many streams in Denali experience debris flows. Also called mud flows, debris flows are fast-moving, rapidly-changing slurries of water and sediment that are capable of carrying huge volumes of material at high velocities. Materials moved by debris flows range in size from clay particles to massive boulders and trees. Debris flows are a common destructive hazard in mountainous regions around the world.

Debris flows are relatively common in Denali, occurring annually on small scales and occasionally on large scales. They can cause catastrophic erosion and deposition along streams and

Above: Heavy equipment works to clear the park road of a slurry of sediment from a debris flow caused by flooding of the small stream at Mile 49.9.

wreak havoc on park infrastructure. Three primary factors make Denali susceptible to debris flows. First, much of the park is sparsely vegetated above 3,000 feet (900 m) elevation, which means there are few roots to stabilize the soil. Second, soils and sediments regularly become saturated with water due to snowmelt, large rainfall events, and permafrost thaw. Lastly, the park has over 20,000 vertical feet (6,000 m) of relief, so there are abundant steep slopes to provide adequate gradients for the flows. Without stabilizing roots to hold steep, saturated soils in place, they occasionally flow downhill, endangering people and infrastructure.

Denali maintenance staff struggle to accommodate debris-flow streams at locations where they cross the park road. Some stream channels in Denali that are 15–100 feet (5–30 m) wide above the road get restricted into culverts only 2–6 feet (0.6–2 m) in diameter when they cross under the road. When large debris flows reach the road, they sometimes plug culverts and deposit materials on the upstream side until the debris overflows onto and over the road, blocking passage. This has been documented many times along this stretch of road, as well as around Sable Pass and Igloo Creek.

MILE Toklat River

53 The Toklat is the largest braided river that is crossed by the Denali Park Road. The vast plain of cobbles, gravel, sand, and silt deposited by the river is a renewable resource. Every other year, large machinery excavates 22,000 cubic yards (17,000 m³) of sediment from the Toklat riverbed for use in resurfacing the park road. Geology and maintenance staff design the excavations to mimic

braided river channels to minimize impacts on natural processes and visual aesthetics.

The park road loses material over time because of erosion, slumping, and dust, and this material must be replaced to maintain a safe surface for travel. Toklat sediment provides a local source for the material, rather than it being imported

from outside the park. This reduces the number of vehicles traveling the road. Using locally-sourced materials also prevents the spread of invasive plants whose seeds can hitchhike to new places when transported from outside the park. Finally, because the material does not need to be purchased and transport distances are shorter, the park saves money and produces less carbon dioxide emissions.

Below: A bulldozer excavates material in the shape of a natural river braid from the Toklat River floodplain. The sediment will be processed into gravel and finer material for use on the Denali Park Road. Note the two large dump truck in the background near the center of the photograph; these trucks can carry 27 cubic yards (21 m³) of material per load.



NPS Photo / Maisie Richards

PART A Park of Unusual **—3—** Scale

Toklat to Kantishna

For a park that is larger than five individual U.S. states, it is only fitting that Denali is filled with landscapes of unparalleled immensity. Here on the final stretch of the park road, the valley opens wide, rewarding visitors with unobstructed views of the Alaska Range and the tallest mountain in North America. The 34-mile long (54 km) Muldrow Glacier, the longest and largest glacier on the north side of the Alaska Range, is just a short hike away from the road. The braidplain of the Thorofare River stretches over a mile wide near Eielson Visitor Center. The road winds past hundreds of kettle ponds towards the popular destination of Wonder Lake and the old mining center, Kantishna. Most notable of all, Denali itself—the tallest mountain in North America at 20,310 feet (6,194 m) high—is only about 30 miles (~50 km) away.

Right: Denali peaks out from above the clouds, as seen from the Eielson Visitor Center.

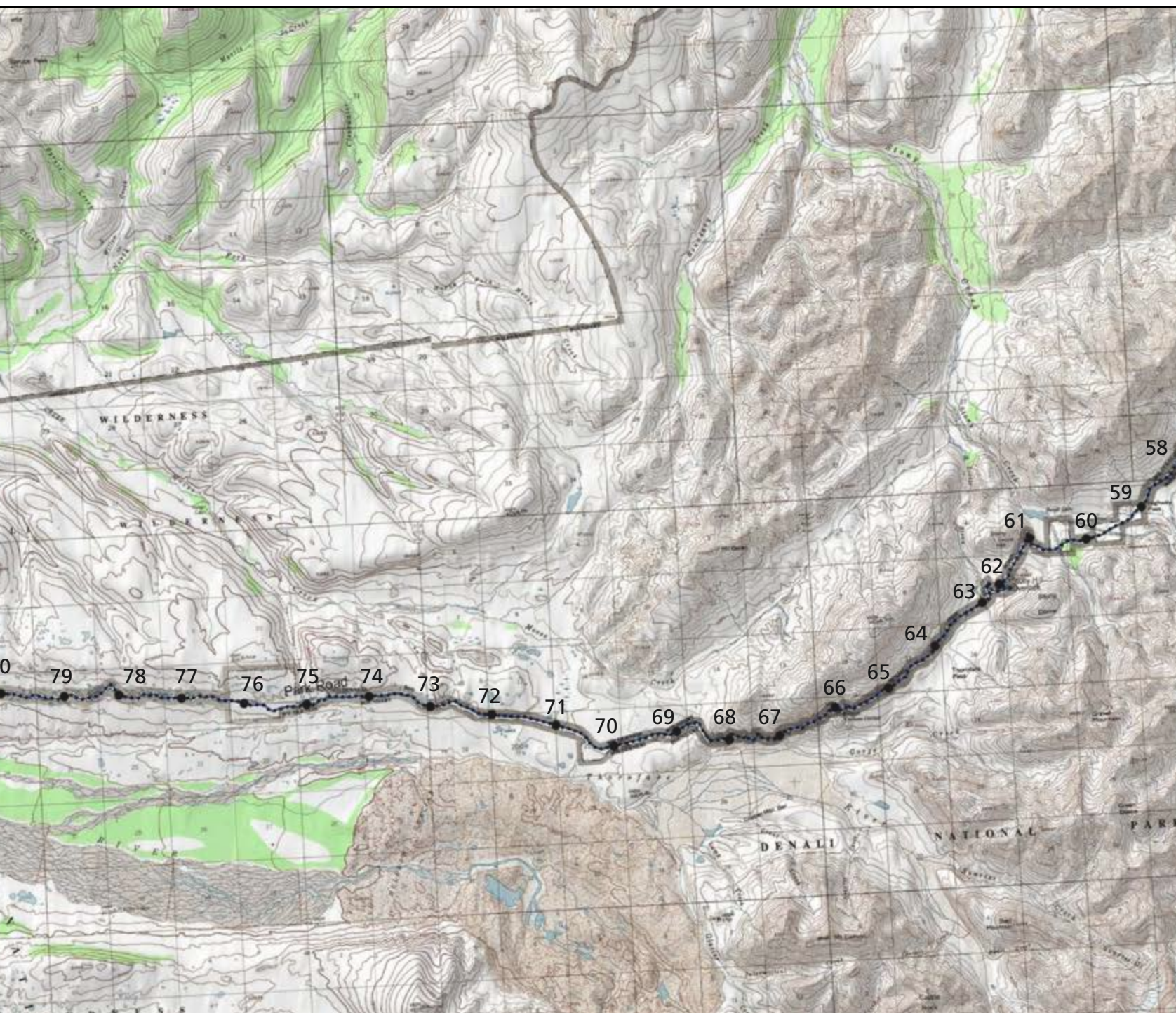


NPS Photo / Tim Rains



<u>Mile</u>	<u>Feature</u>
58.7	Highway Pass
61.1	Bergh Lake
62	Denali Unobscured
67	Eielson Visitor Center
67.5	Pillow Basalt
69–78	Muldrow Glacier
72.4	Hines Creek Fault
75–84	Muldrow Moraines
74–86	Western Kettle Ponds
84–87	Wonder Lake
89–90	Glaciofluvial Terraces
91	Seismic Activity in the Kantishna Hills
92	Kantishna Area Mining Legacy





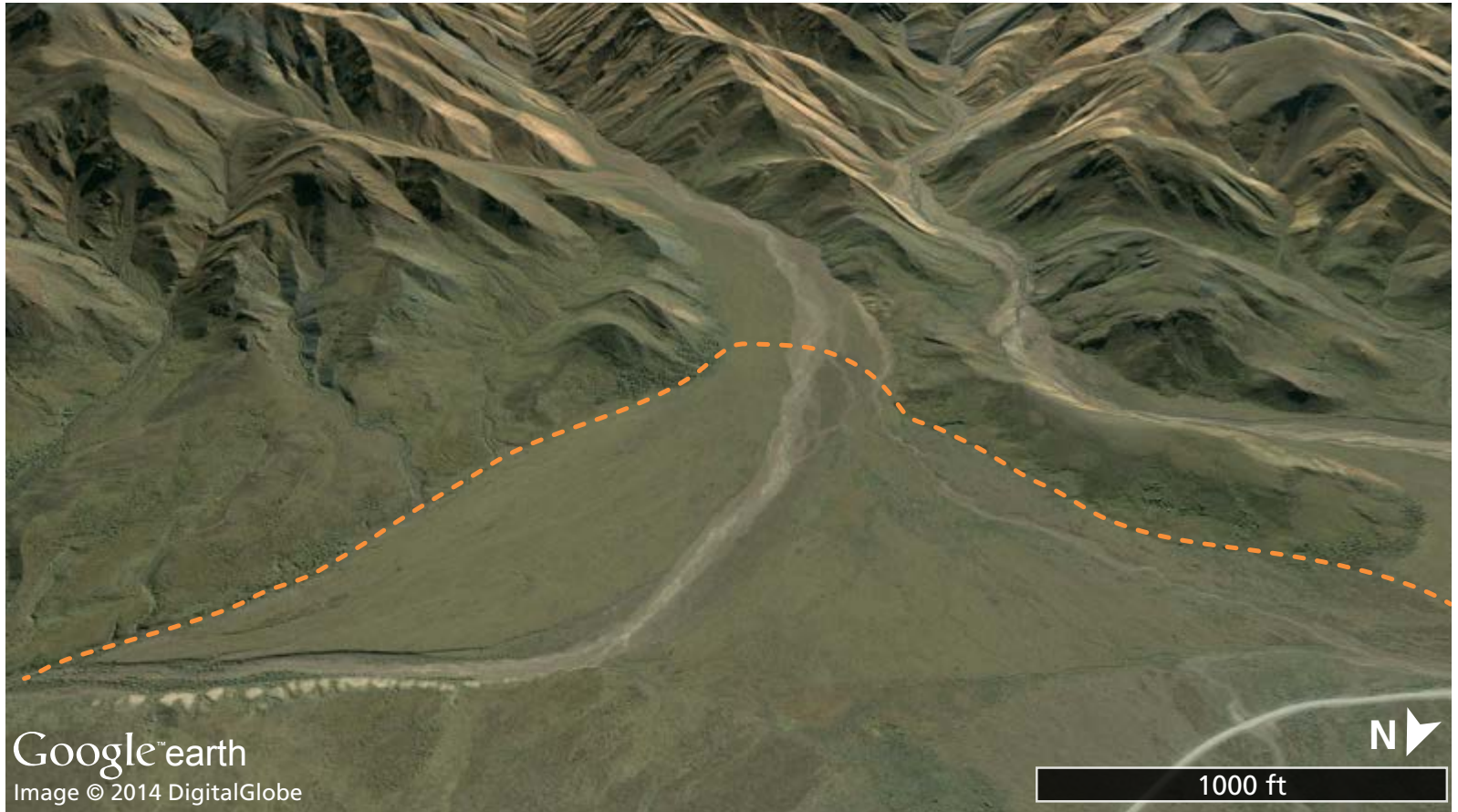
MILE Highway Pass

58.7 Highway Pass is the highest point along the park road at 3,980 feet (1,213 m) in elevation. What makes the area unusual is that an unnamed creek flowing from the south onto the top of the pass forms an alluvial fan that occasionally switches which watershed it feeds. If the main channel of the fan flows to the east, the water drains into unofficially named Highway

Creek, which is a tributary of the Toklat River. If the main channel flows to the west, the water drains into Stony Creek, which is a tributary of the Clearwater Fork of the Toklat River. Regardless of which direction the water flows, it always meets back up at the same location approximately 30 miles (50 km) downstream in the Toklat River.

FUN FACT: At just shy of 4,000 feet (1,220 m), Highway Pass is the third highest maintained road pass in Alaska. Higher road passes include Atigun Pass on the Dalton Highway at 4,739 feet (1,444 m), and MacLaren Pass on the Denali Highway at 4,086 feet (1,245 m).

Below: Oblique Google Earth image of Highway Pass area with the alluvial fan outlined in orange. Note that the majority of the drainage flowed east into the informally named Highway Creek when this image was captured in 2004/2005.

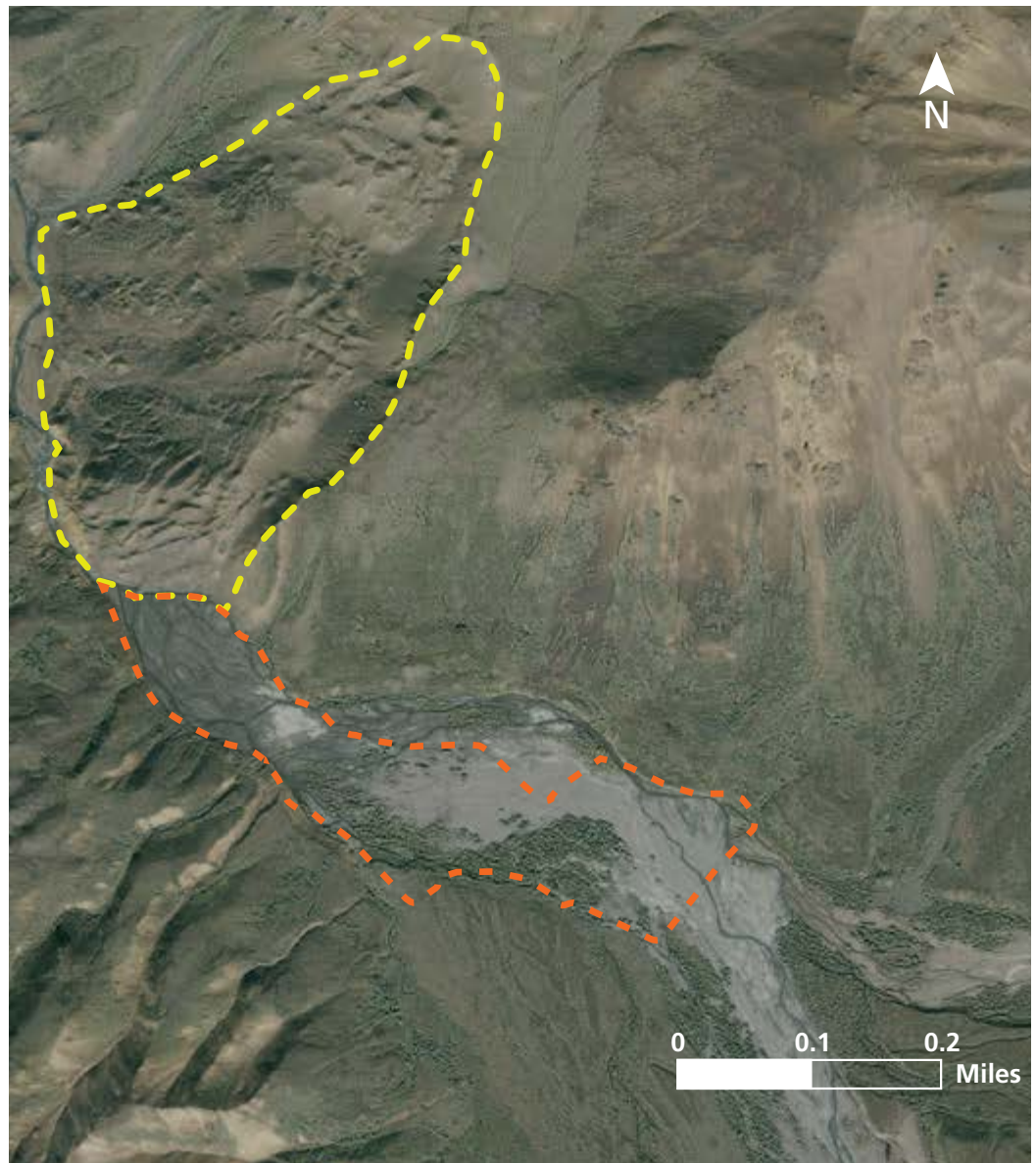


MILE Bergh Lake

61.1 Look around—do you see a lake? According to many maps of Denali, Bergh Lake can be seen approximately one-half mile (1 km) north of the road here. However, in reality Bergh Lake hasn't been here since 1986.

The lake was created when a massive landslide dammed Stony Creek in 1953. In early July of that year, the area experienced unusually heavy rainfall. These rains increased the weight of the soil and the pore pressure of the soil matrix. Then on July 12th an earthquake triggered a landslide on the east side of the valley in fractured basalt. The landslide dammed Stony Creek and a lake began to form¹⁵.

The lake, initially called “Quake Lake,” continued to fill until August 12th and reached a maximum depth of 75 feet before it began to overtop the landslide debris. The lake was officially renamed after Knute Bergh, a pilot with the U.S. Coast and Geodetic Survey; Bergh was mapping in this area that year and was killed in a plane crash. Over subsequent decades Bergh Lake disappeared due to Stony Creek cutting through the landslide debris and filling in the lake with sediment.



Above: 2004/2005 IKONOS satellite image of the Bergh Lake area. The landslide that caused the lake can be seen near the top left (dashed yellow line). The area mapped as Bergh Lake on several topographic maps (dashed orange line) is now a braided stream and vegetated terraces.





MILE Denali Unobscured

62 From Stony Overlook, if the weather is fair, there is a stunning view of Denali unobscured by other peaks 37 miles (60 km) to the southwest. From this perspective it looks like the north peak at an elevation of 19,470 feet (5,934 m) is approximately the same height as the taller south peak at 20,310 feet (6,190 m). This is because of your visual perspective; the north peak is 1.5 miles (2.4 km) closer than the south peak, so it appears taller.

Though Denali and its surrounding mountains are largely composed of granitic rocks, Denali's north peak is capped with a sedimentary rock called Kahiltna Flysch. The flysch formed in a deep oceanic basin approximately 100 million years ago during the Cretaceous Period⁴⁹. Since then it has uplifted not only above sea level, but to almost the top of the highest peak on the continent. Mountaineers thus have the potential to gaze at fossilized sea creatures while standing at the top of North America!

FUN FACT: Denali is still growing by about one millimeter per year³⁸. That may not seem like much, but at that rate it will rise one kilometer (3,300 feet) in the next million years—a brief period in geologic time.

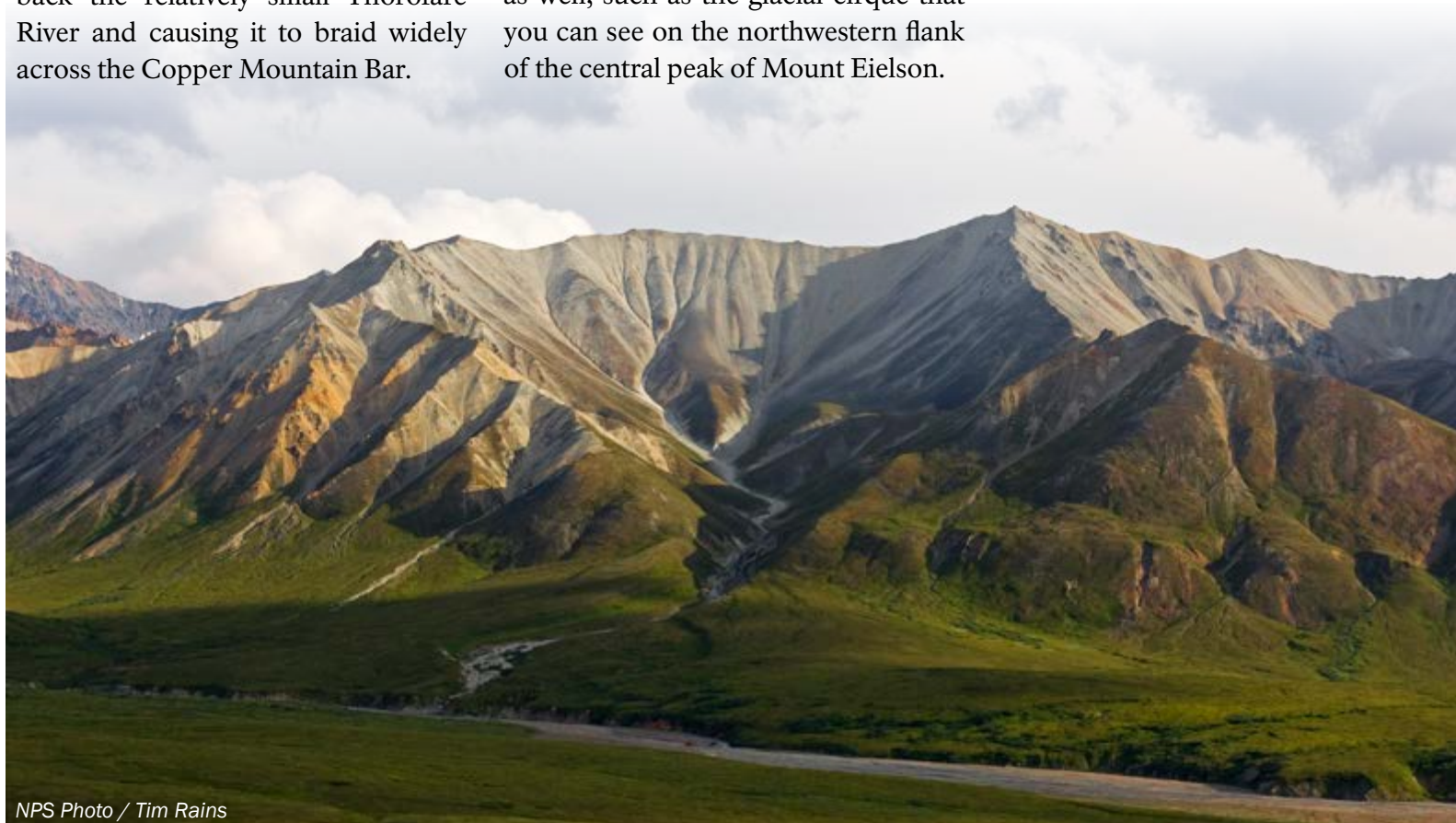
MILE Eielson Visitor Center

67 From the Eielson Visitor Center, a range of different geologic features can be seen even on a cloudy day. The mile-wide (1.6 km) Copper Mountain Bar, with the Thorofare River braiding across it on its journey westward, dominates the foreground below the visitor center. While it is not obvious from this location, the Thorofare River's path is impeded by the Muldrow Glacier to the southwest. The Muldrow acts like a dam, holding back the relatively small Thorofare River and causing it to braid widely across the Copper Mountain Bar.

Glaciers have shaped and continue to shape the landscape around you. Approximately 22,000 years ago, the valley below the Eielson Visitor Center was likely covered in glacial ice that flowed down from the Alaska Range^{27,44}. At present, the glaciers have retreated to where they are barely visible, but they still contribute large amounts of sediment to the Copper Mountain Bar. Signs of their passage punctuate the mountain sides as well, such as the glacial cirque that you can see on the northwestern flank of the central peak of Mount Eielson.

Below: The Eielson Visitor Center looks out on Mt. Eielson. From the roof of the center you can see signs of glaciers and braided rivers, and perhaps catch a glimpse of Denali.

Opposite Page: The view of the Alaska Range from Eielson features Denali and many other glaciated mountains. In this photo, Denali is the mountain on the right and Mount Brooks can be seen on the left.



NPS Photo / Tim Rains

Mount Eielson, formerly known as Copper Mountain, rises prominently to the south of the bar and has a rich geologic and human history. Most of the mountain is composed of granodiorite (similar to granite), an intrusive igneous rock that cooled ~38 million years ago²⁵. Valuable minerals including lead, silver, zinc, and copper occur in veins in Mount Eielson. In 1920, the well-known Kantishna miners Joe and Fannie Quigley staked the first mineral claims here. By 1922, Superintendent Karstens estimated that about 50 claims had been placed in the vicinity of Mount Eielson. Interest in mining the area waxed and waned from the 1920s through the 1960s due to economic and transportation considerations. Finally, the Mining in the Parks Act was passed in 1976 and all existing mining claims were determined to be invalid, bringing mining to an end in this area¹⁵.

The same igneous material from which Mounts Eielson and Foraker formed likely pushed its way to the surface and erupted to form the only known ancient volcano in the park. A trail leads north from the Eielson Visitor Center to what is likely the eroded volcanic vent on Thorofare Ridge. Here, volcanic rocks such as breccias and tuffs have weathered into an exceptionally colorful palette since deposition ~38 million years ago²⁵.

On the rare summer days when the skies are clear, bright-white Denali dominates the scenery to the southwest of Eielson Visitor Center. Many other heavily glaciated mountains are also visible from here. Denali is flanked to the east by Mounts Brooks (11,940 feet/3,639 m) and Silverthrone (13,220 feet/4,029 m). Both of these mountains are composed of Kahiltna

Flysch like the north peak of Denali. To the northwest of Denali is the much lower-elevation granitic Peters Dome (10,571 feet/3,222 m). Even though Peters Dome is less than half the elevation of Denali, glaciers still cover its upper slopes. The Denali Fault is located between Peters Dome and Denali, but cannot be seen directly from any location along the park road.

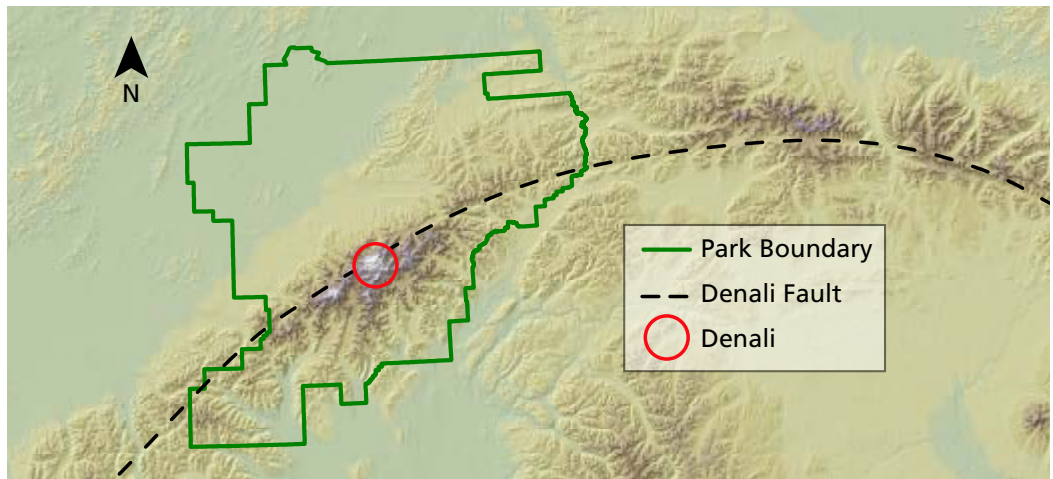


NPS Photo / Tim Rains

GEO Why is **FEATURE** Denali so Tall?

The Alaska Range continues to be affected by the subduction and accretion of tectonic plates under and onto the North American Plate. As subduction occurs, the leading edge of the oceanic plate melts at depth and bubbles up through the overlying continental crust. Around 56 million years ago, this process provided the raw materials and igneous core of much of the Alaska Range²⁰. However the mountain building isn't over yet.

The uplift of the Alaska Range is largely the product of compressional forces associated with the Pacific Plate and Yakutat Block (a terrane that is in the process of accreting to the North American continent along Alaska's southern coast). As they converge with Alaska, they rotate counterclockwise along the Denali Fault, the strike-slip fault that arcs from east to west across much of the state. The slipping, or shearing force, along the fault slows near the apex of the arc at the center of the Alaska Range. At this location, some of the fault's energy manifests as compressional forces that fold and crumple the plates, causing the rocks to be uplifted. While this uplift has been ongoing since the Mesozoic, the vast majority has occurred within the last 6 million years^{22,63}.



Above: Denali's lofty elevation of 20,310 feet (6,190 m) is attributed to subduction and accretion processes that are still pushing up the Alaska Range today, as well as a kink in the Denali Fault that causes focused mountain-building forces.

Even within the central Alaska Range, at 20,310 feet (6,190 m), Denali is anomalously tall. Denali towers almost 3,000 feet (915 m) higher than its neighboring Mount Foraker and almost 6,000 feet (1,830 m) higher than other nearby neighbors. Denali is not a volcano, so what geologic processes created this unique mountain?

This question remains the subject of active research, but it is now widely accepted that the main contributing factor to Denali's elevation is a kink in the Denali Fault called a restraining bend. The kink at the restraining bend restricts the fault's strike-slip movement, which causes focused compressional stress. When the stress is released in an earthquake, it crumples

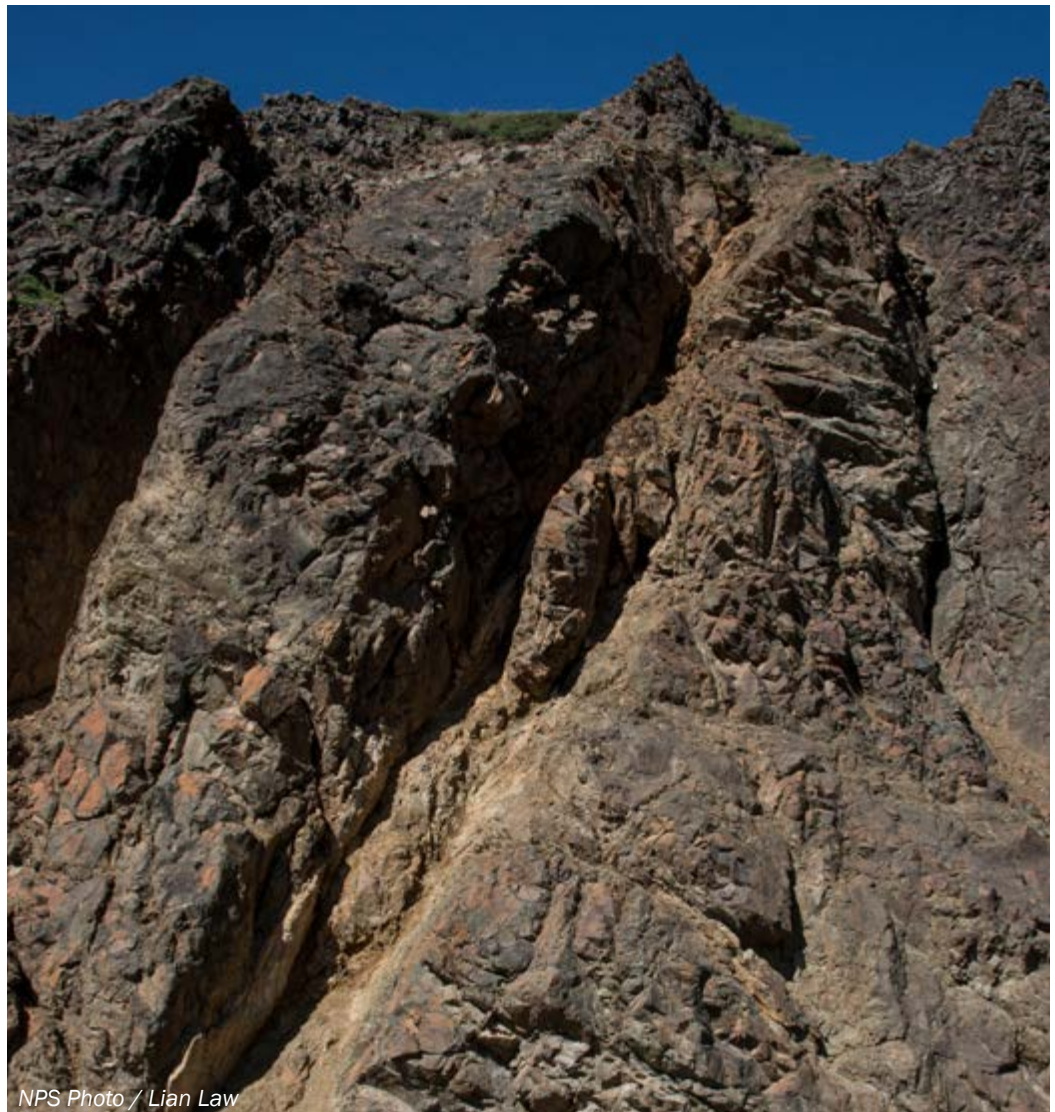
and pushes up the nearby rock. Therefore Denali attains its immense size and lofty elevation because of its location inside the restraining bend⁴¹. Additional factors such as lithology (rock hardness) and isostasy (buoyance of the Earth's crust) also play a role in its elevation, but are thought to have substantially less influence^{6,7}.



MILE Pillow Basalt

67.5 Here the road winds around a dark outcrop of pillow basalt, which is formed during some underwater volcanic eruptions. Pillow basalt occurs when lava squeezes up past previously-cooled structures and creates tear-drop-shaped blobs that quickly cool from their edges inward. The results are rounded, one-to-three-foot-wide (0.3-1 m), packed structures that are darker and finer grained near their edges than in their centers. The pillows are somewhat hard to spot—look for their dark outlines on the outcrops to the north of the road where they have been exposed and are eroding away.

This pillow basalt formed approximately 200 million years ago, possibly on an island arc system similar to the Aleutian Islands or an underwater volcano. Later these rocks were transported by plate tectonics, accreted onto the North American continent, and folded and faulted into their present location^{84,17}.



Above: Cliffs with pillow basalt adjacent to the park road.



Left: The intersection of multiple pillows within the basalt. The triangle-shaped, dark material near the upper-right cooled quickly because of contact with water and separates three visible pillows.

MILE Muldrow Glacier

69-78

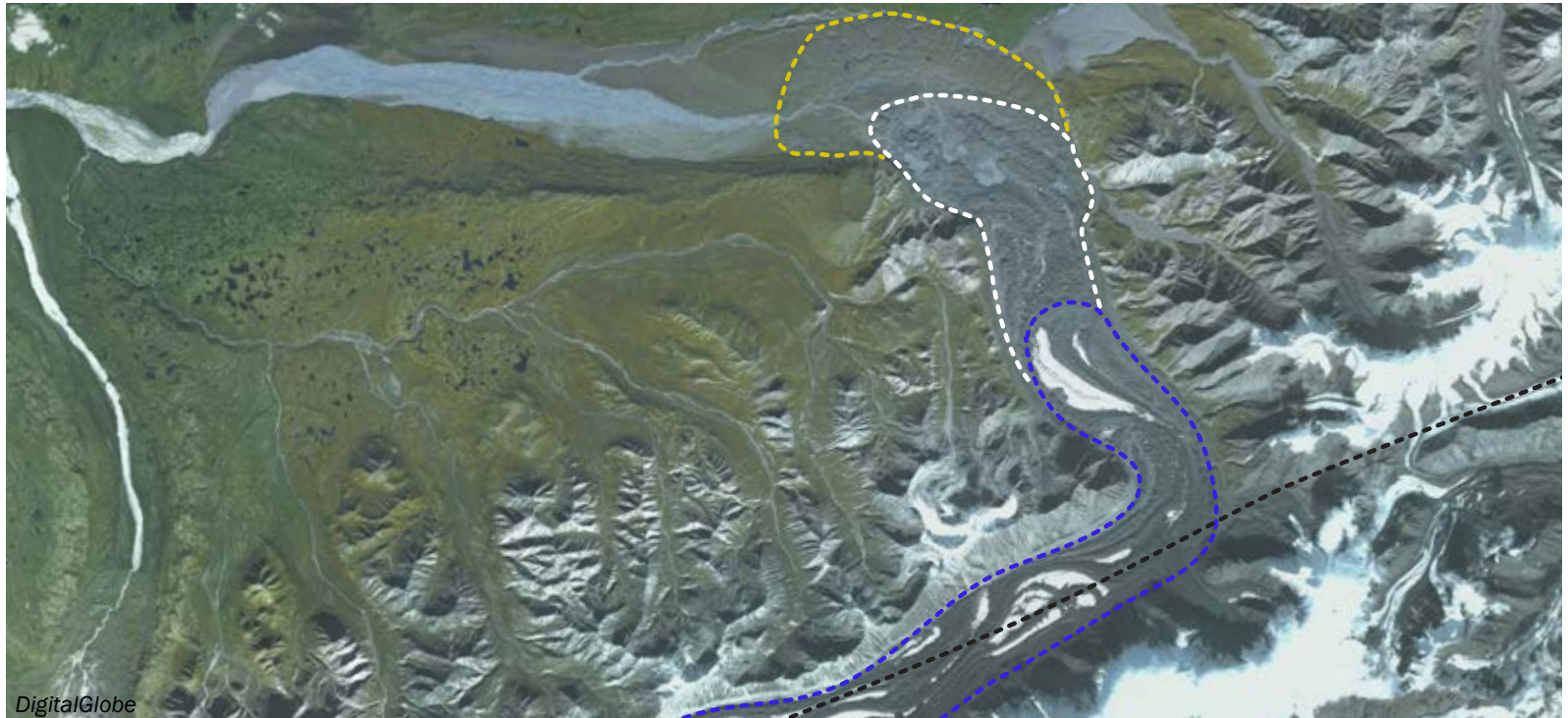
For several miles the road runs parallel to the terminus of the longest glacier (34 miles [54 km] long) on the north side of the Alaska Range, the Muldrow Glacier. Don't look for shiny blue glacial ice, though, because here at the terminus of the glacier the ice is stagnant—unmoving—and covered in tundra. Yes, believe it or not that lumpy, hummocky, shrubby tundra less than a mile away to the south is underlain by ice. While perhaps not as romantically crevassed

and frigid looking as an active glacier face, the vegetated terminus of the Muldrow is fascinating because it is evidence that the glacier surges.

All glaciers flow—that is one of their defining features. Glacial flow is mostly controlled by temperature, snow accumulation, and slope. However, a small minority of glaciers is also substantially affected by subglacial hydrology. Called surging glaciers, these ice rivers

advance with sudden and rapid speed—sometimes as much as 100 times faster than average—after long periods of sluggish movement. The terminus can advance several miles in a year or two, leaving a bathtub ring at the top of the glacial valley where the ice has drained out. Surging glaciers do not experience a net gain in mass during surge events; rather the mass is transferred from up high to down low⁶⁰.

Below: A satellite image of the Muldrow Glacier shows that the ice takes a sharp 90° turn to the left when it leaves the trench of the McKinley Strand of the Denali Fault (black dashed line). The active margin is delineated in blue, the 1956-57 surge margin in white, and older margins in yellow.



DigitalGlobe

The Muldrow is one of four confirmed surging glaciers in Denali out of hundreds of glaciers. The upper 27 miles (42 km) currently flow slowly but constantly downhill as with any 'living' glacier. This movement carries away rocky debris and inhibits the growth of vegetation that might otherwise become established. However, the lower 7 miles (12 km) of Muldrow ice and debris are stagnant, having been deposited during glacial surges as long as 1,800 years ago and not having moved since. Younger moraines were deposited ~900 years ago and during surges in ~1905 and 1956–1957^{26,46,82}. Park geologists and university researchers speculate that the Muldrow may surge again at any time, and therefore monitor for signs of renewed surging.

The terminus of the Muldrow Glacier is an interesting place to go for a hike, although caution is advised while crossing the Thorofare River, which can rise markedly during the heat of the day or due to rain. You can find freshly exposed ice on undercut banks with blueberry bushes growing on top, and sometimes whole amphitheaters of rotting 1,800-year-old ice.

Right: Sediment covers the white glacial ice of the Muldrow Glacier.

The Muldrow Glacier takes a 90° turn as it flows down from the mountains, changing course from primarily east to north. The McKinley Strand of the Denali Fault strongly controls part of the path of the Muldrow, much like the Hines Creek Fault controls part of the path of Hines Creek. Along the east-flowing section, the Muldrow

follows a weakness in the rocks caused by the fault and flows parallel to the mountain front along very steep topography. The sharp zag to the north in the last few miles happens where the glacier frees itself from the relative confines of the fault and flows away from the mountain range like most glaciers.



NPS Photo

MILE Hines Creek Fault

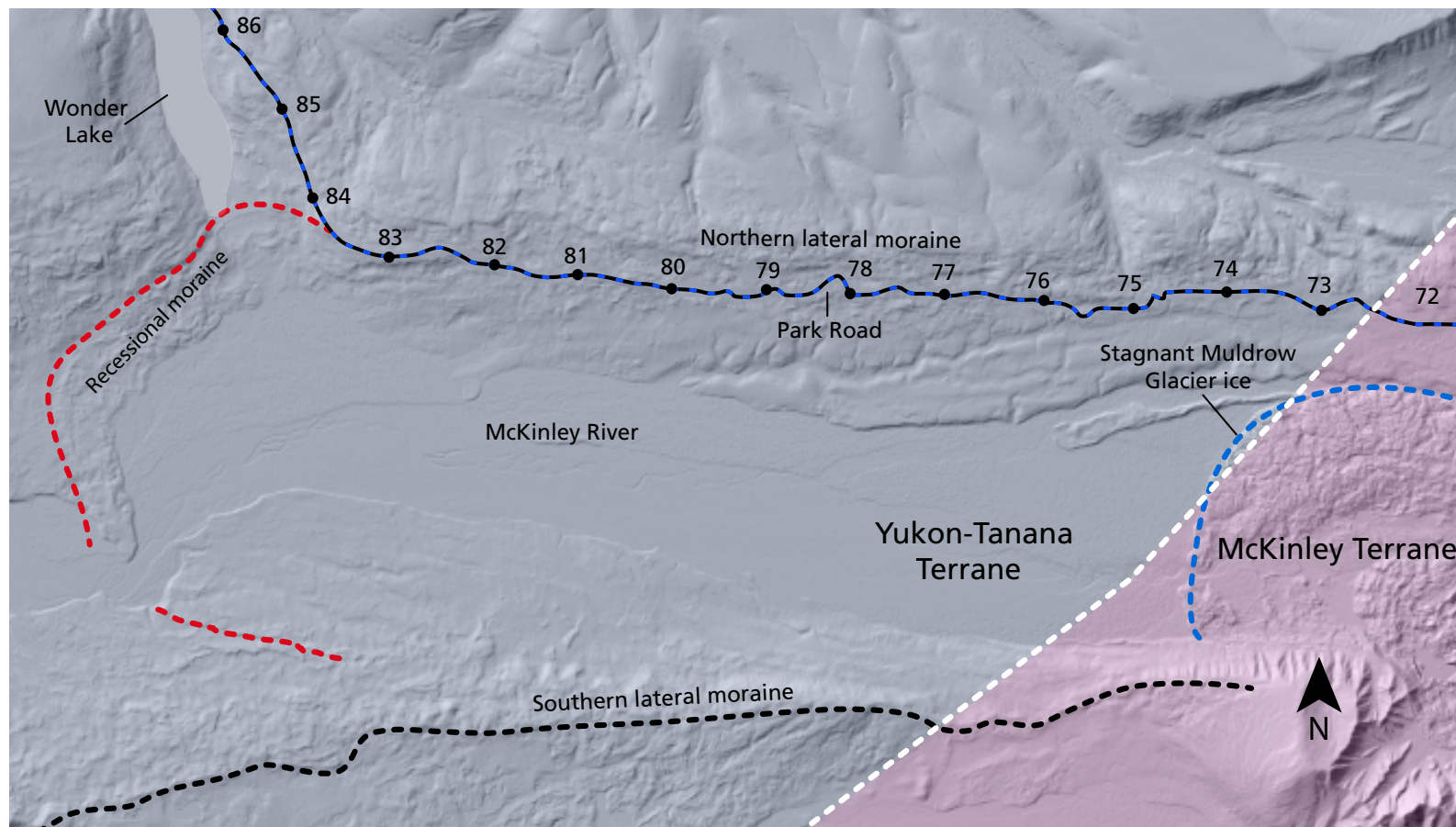
72.4

The park road crosses the Hines Creek Fault near here as you cross back from the McKinley to the Yukon-Tanana Terrane⁶⁹. The thick glacial moraines that were deposited here during the last ice age and other sediments obscure the terranes below them. No evidence of fault-induced movement has been found in these sediments, which could indicate that no major earthquakes have occurred on this fault since their deposition.

Until recently, only older offsets of the Hines Creek Fault had been identified in and around the park. Thanks to recent LIDAR imagery and associated fieldwork, we now know that at least one segment was active ~1,300 years ago³². This geologically-recent event indicates the ongoing potential for future earthquake-induced movement in the area.

Opposite page: The top of the southern lateral moraine of the Muldrow Glacier (white-dashed line) rises above the McKinley River.

Below: 2010 IFSAR digital terrain model of the Muldrow Glacier area. Note the approximate location of the Hines Creek Fault (white-dashed line) between two terranes, the crest of the southern lateral moraine, the crest of the recessional moraine, and the park road.



MILE 75-84 Muldrow Moraines

Across the McKinley River is a long hill paralleling the river at about the same elevation as the road. This is the southern lateral moraine left behind by an advance of the Muldrow Glacier during the most recent ice age. Now guess what hill you're driving on? Indeed, it's the northern twin of that moraine. Around Mile 84, recessional moraines can also be seen to the southwest where they narrow the river and dam Wonder Lake.



Photo by Craig Brandt

MILE **Western**
74-86 **Kettle Ponds**

The sprawling approach to, and region around, Wonder Lake is dotted with kettle ponds. Like the ones near the Teklanika River rest stop, these ponds are remnants of previous glaciations. Look for ducks, shorebirds, and swans swimming in them, and flocks of sandhill cranes using them as a migration stop in the fall.



MILE Wonder Lake

84-87 Do you wonder how it formed? Wonder Lake, 2.6 miles (4.2 km) long and 280 feet (85 m) deep, was excavated by the Muldrow Glacier and then dammed by its recessional moraines (see Muldrow Moraines Mile 75-84). Approximately 22,000 years ago, the Muldrow covered the area now occupied by the lake and formed the moraine that dams

its north end. By ~14,000 years ago the glacier had retreated, leaving behind the recessional moraine that dams the southern end of the lake^{14,26}.

Thanks to a quirk of topography, the inflow and outflow channels of Wonder Lake are located side-by-side at the northern end of the lake. The lake is fed by an unnamed stream that flows

in from the east and crosses under the park road at mile 85.2. It drains just a few hundred feet (~100 m) to the west through Lake Creek.

Below: The stream that feeds Wonder Lake crosses the park road under a causeway visible in the lower left. The outflow channel looks like a thin ribbon snaking westward in the lower right.



NPS Photo / Jake Frank

GEO Earthquakes

FEATURE Earthquakes occur daily in Denali, but most of them are too small for us to feel. The majority occur in the Kantishna area and are caused by small crustal blocks shifting between major faults. Within the park, most of the earthquakes north of the Denali Fault are shallow (less than 20 miles [35 km] deep) and low magnitude (averaging around magnitude 2). In contrast, most of the earthquakes that occur south of the Denali Fault are deeper (45–80 miles [75–125 km] deep) and higher magnitude, with many of the deepest quakes clustering near Denali. These deeper events are caused by the subduction of the Pacific Plate as it dives under the North American Plate. The Pacific

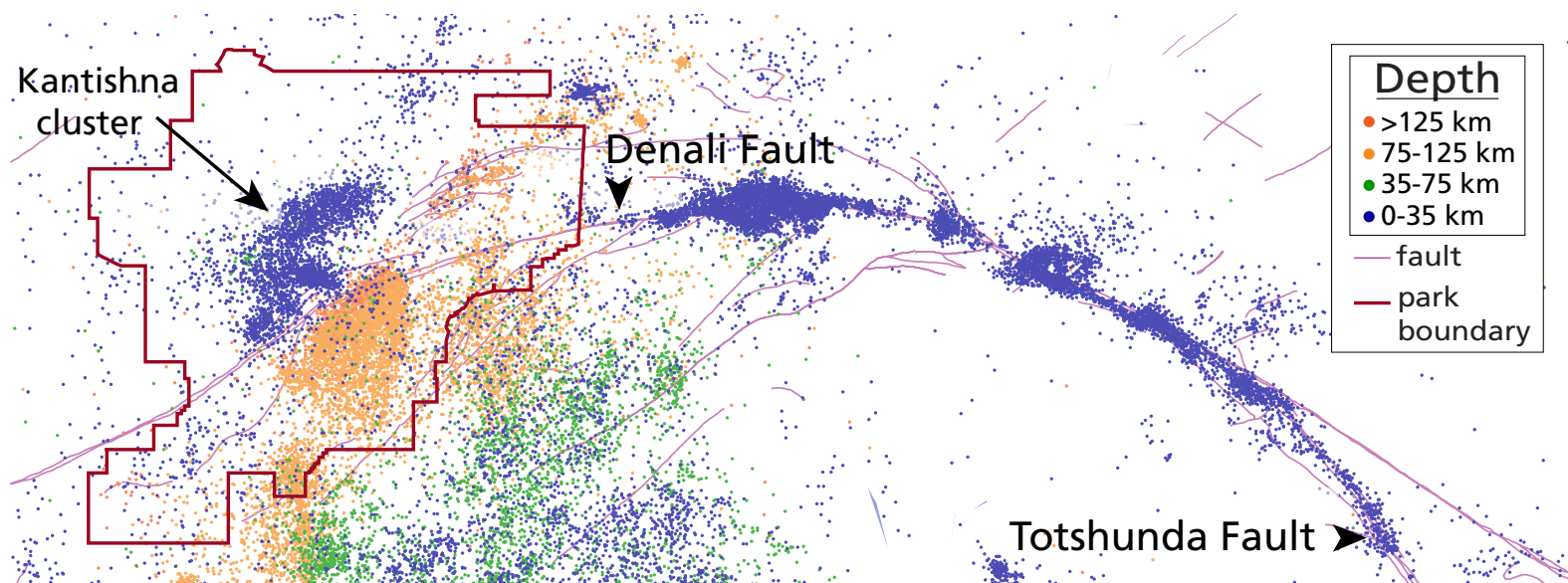
Plate is moving northwest relative to Alaska, causing earthquakes along the interface and contributing to the continuing uplift of Denali².

The highest magnitude events that occur in Denali each year are usually in the low M 4s. Larger magnitude events (> M 4.5) are not common in the park, but are exciting when they happen. In 2002, a M 7.9 earthquake—the largest to occur in the interior of the state in recorded history—ruptured a portion of the Denali Fault east of the park⁶⁶. The main shock occurred about 50 miles (80 km) southeast of the Denali Visitor Center and caused horizontal offsets of up to 29 feet (8.8 m). Although local residents only suffered spilled shelf items and a few road sags, about

100 miles (161 km) east of the park some roads were severely impacted, several homes were jostled off their foundations, and some supports for the Trans-Alaska oil pipeline failed⁷⁷. In the year that followed, over 35,000 aftershocks were recorded along the Denali and associated Totshunda faults⁶⁵. This single earthquake released more energy than all of the earthquakes that have occurred in the lower 48 US states over the last 30 years combined⁸³!

Opposite Page: The Wickersham Dome seismic station has a great view of Denali.

Below: Depths of earthquakes along the Denali Fault from 2007-2011².



When will the next big earthquake occur in Denali? Earthquake forecasting, where scientists predict the probability of a certain magnitude earthquake occurring over years or decades, is difficult in Alaska. Faults are often remote and difficult to access, and relatively few resources are available to study earthquakes here because they tend to have a limited effect on sparse populations compared to other seismically active states. However, it is known that the Denali Fault within the park has not experienced a major earthquake in over a century. Therefore, it is likely that stress is continuing to build and will one day be released in a major earthquake.

Denali collaborates with the Alaska Earthquake Center (AEC) and other groups to monitor and understand seismic activity in Alaska. AEC monitors hundreds of seismometers throughout the state, including four within Denali: 1) Mount Healy near the park entrance, 2) Thorofare Mountain near Eielson Visitor Center, 3) Wickersham Dome in Kantishna, and 4) Castle Rocks in the west of the park. The data from these stations is transmitted to Fairbanks and uploaded to the internet automatically every second.



Photo by AEC

MILE 89-90 Glaciofluvial Terraces

To the south you'll see a flat-topped terrace that is incised by Moose Creek. This terrace is comprised of outwash sediments from the Muldrow Glacier that were deposited when the terminus of the glacier was near here around 22,000 years ago^{27,44}. The terrace at mile 89 is above road level, while at Mile 90 it is approximately at road level.

Right: 1983 oblique airphoto of the glaciofluvial terrace adjacent to Moose Creek near Mile 89.

Below: 2015 oblique satellite image of the glaciofluvial terrace adjacent to Moose Creek. The terrace resembles a gray table top (marked by white-dashed line) bisected by green runoff channels.



FUN FACT: Glaciofluvial terraces are rich sources of gravel in the park, around Alaska, and in other previously-glaciated areas. Most of the gravel that is used to maintain the park road, besides that which is extracted from the Toklat River, is mined from glaciofluvial terraces including the one pictured above.

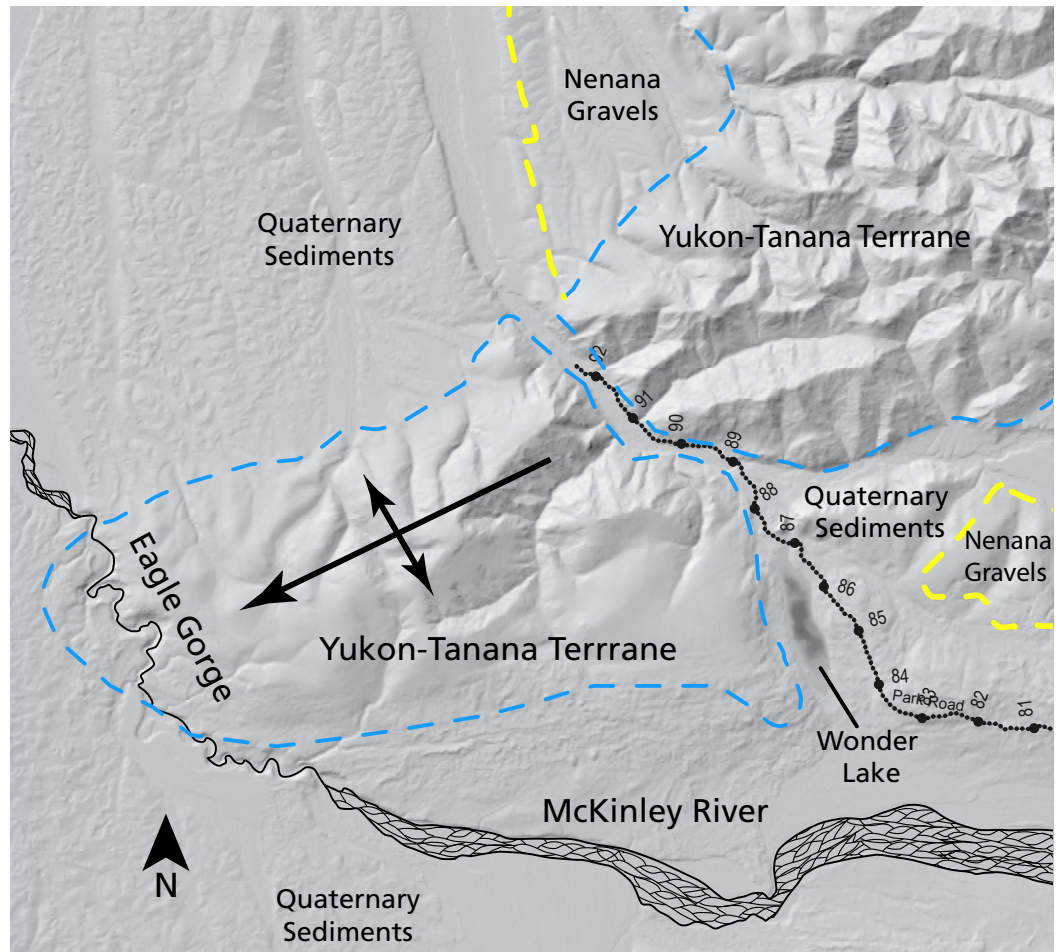


MILE 91 Seismic Activity in the Kantishna Hills

The Kantishna Hills area is the most seismically-active region in interior Alaska, with thousands of low magnitude, shallow earthquakes occurring here every year. The area is seismically active because it lies at the intersection of the strike-slip Denali Fault and two seismic zones—Minto Flats and Susitna—that are being offset in different directions⁶⁶.

Gold, silver, antimony, lead, zinc, copper, and other minerals have been mined in Kantishna over time. Past tectonic events created a long, linear, upward-folded bedrock layer (made of the same Yukon-Tanana Terrane that is found near the park entrance) called an anticline. Upward pressure forced the anticline to fracture in places, which allowed hydrothermal fluids rich in valuable elements to percolate towards the surface. These fluids subsequently cooled into veins of ore¹⁸.

The Kantishna anticline is thought to be actively rising, as evidenced by the McKinley River constricting from a highly braided floodplain to a canyon and then back to a braided floodplain after it crosses the anticline in Eagle Gorge. The river is cutting through the rising anticline similar to how Denali's antecedent streams cut through the Outer Range⁶⁶ (see Mile 22.8).



FUNFACT: Look south across Moose Creek from approximately Mile 91.7 and you'll see a small adjacent stream channel with an orange coating on its bottom. The color is caused primarily by iron oxidation of the same types of minerals that drew miners to the area.

Above: Annotated IFSAR digital terrain model of the Kantishna area. Note how narrow the McKinley River is as it passes through Eagle Gorge. There, the river is incising through a plunging anticline. Arrows indicate slope direction of Yukon-Tanana Terrane schists. The anticline continues to rise and the river cuts down through it⁶⁶.

MILE 92 Kantishna Area Mining Legacy

Gold was discovered in the Kantishna Hills by Judge Wickersham of Fairbanks and his climbing party after their failed attempt to summit Denali in 1903. From 1904 through the 1980s, a steady stream of prospectors scoured the area for gold, silver, and associated valuable ores. While the number of prospectors that worked claims in the area probably peaked during the stampede of 1905, the greatest value of ore was extracted in the 1970s and 1980s due to the availability of heavy machinery and improved access to the area⁶⁷.

Early prospectors mostly separated the gold from stream deposits by hand using pans and sluice boxes (troughs with grooves along the bottom). Later on, much larger volumes of placer deposits were mined mechanically using redirected stream water, heavy machinery, and occasionally hydraulic giants (high-pressure water cannons). Miners also traced upstream from rich placer deposits and used lode mining techniques, which removed bedrock and the source ore deposits⁶⁷.

Right: Kantishna miners observing the first hydraulic mining on Moose Creek (year unknown) .

Cumulatively it is estimated that 55,000 ounces of gold, 265,000 ounces of silver, five million pounds of antimony, and 1.5 million pounds of combined lead and zinc were removed from the Kantishna Hills through 1978¹⁶.

Early miners left behind a footprint of altered stream channels and tailings piles, but the most extensive environmental degradation was

caused by miners using heavy bulldozers, excavators, front loaders, and mechanized sluice boxes. Mining ceased in 1985 with the passage of a federal mining injunction that requires an environmental assessment demonstrating that mining activities do not have an adverse impact on

FUN FACT: Thirty men produced 1,000 ounces of gold in the Kantishna area during 1975⁵⁷.



DENA 22184: DNP & P Museum Collection



NPS Photo

Above: Heavy machinery loads gold-bearing stream sediments into a sluice box for separation at Eureka Creek in 1984.

the environment. Since then almost all of Kantishna's mining claims have been purchased or invalidated. Most of the remaining claims have thus far not been developed for mining purposes⁵⁷.

Mining reclamation efforts in the area began in the late 1980s and

continue today. Placer mining restoration includes flattening tailings piles, recontouring flood plains, restoring channels to natural sinuosity, and replanting natural vegetation³¹. Lode mining reclamation techniques include treating acid mine drainage and blocking mine entrances

for safety⁵⁷. Despite reclamation efforts, the water from most streams and some wells in the Kantishna area is not potable because of high arsenic, iron, and antimony levels⁸. In some places this is due to mining activity, while in other streams these elements occur naturally.

Geologic Timeline

Era	Period	Epoch	Age (Ma)*	Glaciation and Rock Formations
Cenozoic	Quaternary	Pleistocene	2.6 - 0.01	Riley Creek Glaciation (~22 ka**) ^{27, 14}
				Healy Glaciation (~65 ka) ^{5, 27, 14}
				Browne Glaciation (>300 ka) ²⁷
				Lignite/Dry Creek Glaciation (~500 ka) ⁴²
	Tertiary	Pliocene	5.3-2.6	Teklanika Glaciation (~2.8 Ma) ^{44, 72}
				Nenana Gravel Formation (~2.8-5.4 Ma) ^{1, 61}
		Miocene	23 - 5.3	Usibelli Group of Formations (~5-23 Ma) ⁶¹
		Oligocene	34 - 23	
		Eocene	56- 34	Mt Galen Volcanics (~38 Ma) ²⁵
Mesozoic	Cretaceous		146-66	Mount McKinley Granite (~56 Ma) ²¹
				Teklanika Formation (56-60 Ma) ²¹
	Jurassic		202-146	Cantwell Formation (71-72 Ma) ⁷³
	Triassic		251-202	Kahiltna Flysch Formation (80-140 Ma) ⁴⁹
Paleozoic			542-251	Yukon-Tanana Terrane accreted (~195 Ma) ^{3, 45}
				Yukon-Tanana Terrane rocks formed (~400 Ma) ^{23, 28}

Note: This is not a comprehensive list of glacial advances and rock formations, but rather a summary of those referenced in this guide book. Glaciation dates indicate maximum ice extents.

* Ma = megaannum or million years.

** ka = kiloannum or thousand years.

A **Accretion** - A process that adds part of one tectonic plate to another plate along a convergent plate boundary.

Alluvial Fan - A fan-shaped landform of sediment that forms where a mountain stream enters a valley.

Antecedent stream - A stream that maintains its course despite changes in bedrock topography.

Antimony - An element named after the Latin word Stibium. It has been used in paint and is highly toxic to humans and wildlife.

Andesite - Fine-grained, generally dark-colored volcanic rock containing more silica than basalt.

Aufeis - A mass of layered ice that forms when groundwater flows up through existing ice at freezing temperatures. Also called overflow ice.

Basalt - A dark, fine-grained, volcanic rock with a low silica content, but rich in iron, magnesium and calcium.

Bedrock - The solid rock that lies beneath soil and other loose surface materials.

Breccia - Rock made up of angular fragments of other rocks held together by mineral cement or a fine-grained matrix.

C **Cantwell Formation** - An approximately 70-million-year-old sedimentary formation, formerly called the Lower Cantwell Formation.

Ceratopsian - A beaked, horned dinosaur of the Cretaceous Period.

Cirque - A mountain feature formed through glacial erosion that is steep-sided and half-open like an amphitheater.

Clast - A fragment of a preexisting rock or fossil embedded within another rock.

Conglomerate - A sedimentary rock made of rounded rock fragments such as pebbles, cobbles, and boulders, in a finer-grained matrix.

Coprolite - Fossilized dinosaur dung.

D **Debris Flow** - A type of landslide made up of a mixture of water-saturated rock debris and soil with a consistency similar to wet cement. Debris flows move rapidly downslope under the influence of gravity.

Deposit - An accumulation of sediment.

Dike - A sheet-like igneous intrusion that cuts across layers of a preexisting rock.

Drainage - A channel that carries water.

E **Esker** - A ridge of sediment deposited by streams running under or through a stagnant glacier.

F **Fault** - A fracture in the Earth along which one side has moved relative to the other. Sudden movements on faults cause earthquakes.

Fluvial - A term used to describe river or stream-related features or processes. Fluvial deposits are sediments deposited by the flowing water of a stream.

Foliation - A layering characteristic of some metamorphic rocks. Foliation occurs when pressure squeezes flat or elongates minerals so that they become aligned. These rocks develop a platy or sheet-like structure.

Fracture - Any break in rock along which no significant movement has occurred.

Glossary

G **Glacial Erratic** - A rock deposited by a receding glacier. Erratics vary in size from small pebbles to large boulders.

Glaciofluvial - Relating to streams formed from glacial meltwater.

Glacial Outwash - A deposit of sediment formed below a glacier by meltwater streams.

Granitic - A general term for intrusive igneous rocks that look similar to granite but may range in composition from quartz-diorite to granite.

Gravel - Sedimentary particles 2-64 mm in size.

Hydrology - The science that deals with water on and beneath the Earth's surface. **H**

Igneous - Rock formed when molten rock (magma) cooled and solidified (crystallized). Igneous rocks are classified as intrusive, or plutonic, if they cool and solidify slowly beneath the Earth's crust. They are called extrusive, or volcanic, if they cool quickly at or very near the Earth's surface.

Intrusion - Emplacement of magma (molten rock) into preexisting rock. Dikes are an example of intrusions.

Isostasy - The equilibrium between parts of the earth's crust. The crust floats on the mantle and rises if materials (such as ice) are removed and sinks if materials (such as magma) are deposited.

Kettle Pond - A pond formed when blocks of glacial ice melt and leave behind a depression that fills with water. **K**

L **Landslide** - Downslope movement of rock, soil, and mud.

LiDAR - Stands for Light Detection and Ranging. Similar to radar but uses light from a laser.

Lithology - The study of the physical characteristics of rocks.

Metamorphic - Rock that has undergone chemical or structural changes due to an increase in heat or pressure, or by replacement of elements by hot, chemically-active fluids. **M**

Moraine - A landform composed of sediment that was deposited by a glacier. An end moraine forms at the terminus of a glacier. A terminal moraine forms at the farthest advance of the glacier. Lateral moraines form along the sides of a glacier. Recessional moraines are built during a minor readvance or substantial standstill after the glacier has receded from a greater extent

O **Ore** - A mineral deposit that can be mined at a profit.

Oxidation - Removal of electrons from an atom or ion, usually by combining with oxygen ions. Minerals exposed to air may oxidize as a form of chemical weathering.

Paleocurrent - A flow of water in the geologic past. **P**

Permafrost - A subsurface layer of soil or rock that is continuously frozen for two years or more by natural processes.

Pluton - A large body of intrusive igneous rock that solidified within the crust.

Pyroclastic - Relating to or consisting of rock erupted from a volcano.

R

Relief - Refers to differences in elevation of different points.

Rhyolite - A volcanic rock chemically equivalent to granite. Usually light colored, very fine-grained, or glassy-looking.

Scarp - A cliff formed by faulting, erosion, or landslides.

Sedimentary - Rock formed from preexisting rock or pieces of once-living organisms. Sedimentary rocks form from deposits that accumulate on the Earth's surface, and often have distinctive layering or bedding.

Sediment - Loose, uncemented pieces of rock or mineral.

Silt - Loose particles of rock or mineral. Silt is finer than sand, but coarser than clay.

Slump - A type of landslide in which a mass of rock or soil breaks along a surface and moves downslope.

Solifluction Lobe - A tongue-shaped lobe that formed as sediments flow downhill at different rates.

Striation - A linear mark or scratch on the surface of a rock.

S

Strike-slip Fault - A fault in which the blocks are displaced primarily in a horizontal direction, parallel to the line of the fault.

Subduction - The process of one crustal plate sliding down and below another crustal plate as the two converge.

T

Taiga - The coniferous forests of high northern latitudes.

Teklanika Formation - A tertiary (55-60 million-year-old) volcanic formation, formerly called the Upper Cantwell Formation.

Terrane - A rock formation or assemblage of rock formations that share a common geologic history. A geologic terrane is distinguished from neighboring terranes by its different history, either in its formation or in its subsequent deformation and/or metamorphism. Terranes are separated by faults.

Till - Unsorted, unstratified rock rubble or debris carried on or deposited by the ice of a glacier.

Tuff - Volcanic rock made up of rock and mineral fragments in a volcanic ash matrix.

Tundra - Treeless regions in the arctic and subarctic that are often underlain by permafrost.

Unconsolidated - Loose sediment; lacking cohesion or cement.

V

Vein - A mineral-filled fracture or fault in a rock.

U

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Index

A Accreted terranes 26
 Alaska Earthquake Information Center 79
 Alaska Rail Commission 43
 Alaska Range 1, 7, 10, 18, 19, 56, 60, 68, 70, 72
 Alaska Road Commission 47
 Alluvial fan 64
 Andesite 4, 32
 Antecedent Stream 23, 81
 Antimony 82, 83
 Arsenic 83
 Atigun Pass 64
 Aufeis 22

Basalt 4, 32, 44, 50, 65, 71
 Bear Cave Slump 46, 51
 Bergh Lake 65
 Beringia 56
 Bones 34
 Braided Rivers 15, 16, 59, 68
 Breccias 69
 Brooks Range 6
 Browne Glaciation 7, 8, 84

C Cantwell Basin 32
 Cantwell Formation 4, 20, 28, 29, 32, 34, 35, 36, 37, 84
 Capps, Stephen R. 39, 57
 Castle Rocks 79
 Cathedral Mountain 28, 32
 Ceratopsian 34
 Cirque 57, 68
 Clasts 19
 Copper 69
 Copper Mountain Bar 68
 Cretaceous 19, 20, 29, 34, 35, 36, 37, 67, 84

B

D Dalton Highway 64
 Debris flow 58
 Denali (the mountain) 5, 12, 18, 19, 60, 67, 68, 69, 70, 78, 82
 Denali Fault 10, 27, 69, 73, 78, 79
 Denali Highway 64
 Denali Visitor Center 22, 78
 Dikes 30, 33
 Double Mountain 2, 12, 19
 Drunken forest 2, 24

Earthquake 65, 70, 74, 78, 79, 81
 East Fork Coal Mine 43
 Eielson Visitor Center 15, 60, 62, 68, 69, 79
 Eocene 20, 84
 Erosion 15, 16, 17, 42, 58, 59
 Eureka Creek 83

F Fairbanks 6, 36, 79, 82
 Farewell Terrane 27
 Fossil 34, 35, 37

Giant bison 56
 Glacial Erratics 1, 2, 8, 53, 56
 Glaciation 10, 16, 25, 76
 Glacier 1, 7, 8, 11, 14, 15, 16, 25, 42, 53, 56, 57, 60, 68, 69, 72, 73, 74, 75, 77, 80
 Glaciofluvial Terraces 80
 Gossan 2, 13
 Granite 4, 8, 19, 20, 69,
 Granodiorite 69
 Gravel 4, 14, 15, 18, 32, 42, 59, 80

E

G

H Healy 6, 7, 18, 79
 Healy Glaciation 7, 84
 Highway Creek 64
 Highway Pass 64
 Hines Creek Fault 1, 10, 27, 28, 73, 74

Ice wedge polygon 55
 Igloo Creek 36, 40, 58
 Igloo Creek Debris Slide 40, 42, 46, 51
 Igneous rocks 4, 6, 28, 33, 69
 Intrusions 33
 Iron 13, 44, 81, 83

Judge Wickersham 82

K Kahiltna Flysch 4, 27, 67, 69, 84
 Kantishna 60, 69, 78, 81, 82, 83
 Kantishna Hills 62, 81, 82
 Karpilo, Ron 39, 57
 Kettle Ponds 25, 53, 57, 60, 76

Lake Creek 77
 Lake Moody 7
 Landslides 10, 29, 39, 44, 48, 49, 65
 Lateral moraines 56, 74, 75
 Lead 13, 69, 81, 82
 Lignite coal 18
 Lignite/Dry Creek Glaciation 7, 11, 14, 84
 Limestone 4
 Lithology 18, 70
 Lower Cantwell 28

M MacLaren Pass 64
 Magma 4, 5, 20, 33
 Magnoavipes denaliensis 37
 Mammoths 56

I

L

Marble 5
 McKinley pluton 20
 McKinley Terrane 27, 74
 Metamorphic rocks 5, 17
 Mining 29, 43, 60, 69, 82, 83
 Mining in the Parks Act 69
 Miocene 18, 84
 Moose Creek 80, 81
 Moraine 7, 11, 14, 56, 73, 74, 75, 77
 Mount Brooks 68, 69
 Mount Eielson 69
 Mount Healy 6, 79
 Mount Margaret 6
 Mount McKinley Granite 4, 19, 20, 84
 Mount St. Helens 19, 21
 Mount Wright 6
 Muldrow Glacier 27, 56, 60, 68, 72, 73,
 74, 75, 77, 80
 Murie, Adolf 53
 Murie Science and Learning Center 36

Nenana Canyon 7
 Nenana Gravel 4, 18, 84
 Nenana River 7, 11
 North American Plate 26, 27,
 70, 78

O Obsidian 28
 Outer Range 1, 6, 23, 81

Pacific Plate 26, 70, 78
 Paleocene 20, 32, 84
 Park Headquarters 7, 8, 9, 56
 Parks Highway 6, 10
 Permafrost 1, 9, 24, 38, 39, 40,
 41, 42, 44, 45, 47, 48, 53,
 55, 58
 Peters Dome 69

Pillow basalts 50, 71
 Pingston Terrane 10, 27
 Plains of Murie 53
 Pleistocene 7, 53, 56, 84
 Pliocene 84
 Polychrome Overlook 15, 44, 47, 51, 53,
 54, 56, 57
 Pretty Rocks 48, 49
 Pyroclastic flow 20, 32

Quake Lake 65
 Quaternary 81, 84
 Quigley, Fannie 69, 82
 Quigley, Joe 69, 82

R Rhyolite 4, 19, 32, 44
 Riley Creek 10
 Riley Creek Glaciation 7, 25, 84
 Ruth Glacier 57

Sable Pass 42, 58
 Sable Pass Debris Slide 42
 Sanctuary River 9, 23, 24
 Sandstone 4, 42
 Savage River 6, 14, 15, 16, 17, 18, 23, 57
 Savage Rock 17
 Schist 5, 17, 81
 Sedimentary rocks 4, 18, 28, 29, 32, 42,
 67
 Shale 4
 Silver 13, 69, 81, 82
 Slump 29, 41, 42, 46, 48, 51
 Solifluction lobes 53
 Spheroidal Weathering 50
 Stony Creek 64, 65
 Stony Overlook 67
 Stream deposition 10
 Subduction 26, 70, 78

Sugarloaf Mountain 6
 Suntrana Formation 43

T Tanana Basin 18
 Tattler Creek 30, 37
 Teklanika Formation 4, 19, 20,
 28, 29, 32, 33, 40, 41, 44, 46, 50,
 51, 84
 Teklanika Glaciation 7, 84

Teklanika River 22, 23, 27, 28, 76
 Teklanika volcanism 20
 Terminal moraines 7, 11, 56
 Tertiary 19, 84
 Theropod 34, 36, 37
 Thorofare Mountain 79
 Thorofare Ridge 69
 Thorofare River 60, 68, 73
 Toklat River 30, 59, 64, 80
 Trans-Alaska oil pipeline 78
 Triassic 84

U Upper Cantwell 28
 U-shaped valley 16, 57
 Usibelli Coal Mine 18
 Usibelli Group 4, 18, 42, 43, 84

V-Z Volcanic rock 19,
 20, 32, 44, 50, 51, 69
 Volcano 4, 19, 32,
 69, 71
 V-shaped valley 16,
 17, 57

Wickersham Dome 79
 Wonder Lake 12, 27, 57, 60, 75, 76, 77
 Wrangell-St. Elias 27
 Yakutat Terrane 27
 Yukon-Tanana Terrane 5, 6, 10, 17, 18,
 27, 28, 29, 74, 81, 84
 Zinc 13, 69, 81, 82

Denali National Park & Preserve **GEOLOGY ROAD GUIDE**

The Denali Park Road winds through some of the most exciting geological landscapes on Earth. Whether you are embarking on an adventure, returning from a memorable trip, or simply curious to know more about the incredible science stories hidden amongst our mountains, this guide is for you.

This guide explains intriguing geological phenomena that can be viewed from the park road: faults that cause some of the largest earthquakes in the world, landslides that may be caused by thawing permafrost, rock outcrops so rich with dinosaur footprints that they look like dance floors, and of course, the tallest mountain in North America. Denali's treasure trove of geologic processes and features is unpacked here in a way that any curious reader will find fascinating.

